Mineta Transportation Institute Publications

11-2022

Does Transit Service Reliability Influence Ridership?

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Recommended Citation
Srinivas S. Pulugurtha, Raunak Mishra, and Sravya L. Jayanthi. "Does Transit Service Reliability Influence Ridership?" *Mineta Transportation Institute Publications* (2022). https://doi.org/10.31979/mti.2022.2118

Project 2118 | November 2022

SJSU SAN JOSÉ STATE UNIVERSITY

MTI MINETA TRANSPORTATION INSTITUTE

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Mineta Transportation Institute

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Report 22-40

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November 2022

A publication of the
Mineta Transportation Institute
Created by Congress in 1991

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

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. 22-40	**2. Government Accession No.**	**3. Recipient's Catalog No.**

4. Title and Subtitle
Does Transit Service Reliability Influence Ridership?

5. Report Date
November 2022

6. Performing Organization Code

7. Authors
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8. Performing Organization Report

9. Performing Organization Name and Address
Mineta Transportation Institute
College of Business
San José State University
San José, CA 95192-0219

10. Work Unit No.

11. Contract or Grant No.
69A3551747127

12. Sponsoring Agency Name and Address
U.S. Department of Transportation
Office of the Assistant Secretary for Research and Technology
University Transportation Centers Program
1200 New Jersey Avenue, SE
Washington, DC 20590

13. Type of Report and Period Covered

14. Sponsoring Agency Code

15. Supplemental Notes

16. Abstract

This research focused on analyzing the association between transit service reliability indicators and ridership. Further, the effect of road network, demographic, socioeconomic, and land use characteristics on transit service reliability was analyzed. The analysis was conducted at a bus stop level. Bus arrival/departure and ridership data from the Charlotte Area Transit System (CATS) was obtained. The road network, demographic, socioeconomic, and land use characteristics were captured within 0.25-mile and 0.50-mile buffers. Pearson correlation analysis was conducted to understand the association between road network, demographic, socioeconomic, and land use characteristics and bus transit service reliability measures. The results show that bus transit service reliability has a substantial impact on ridership and is influenced by road network, demographic, socioeconomic, and land use characteristics within the bus stop vicinity. The findings help public transportation agencies to effectively utilize available resources, plan, and provide equitable services to all riders.

17. Key Words Transit, Reliability, Ridership, Road network, Demographic, Socioeconomic, Land use characteristics, Correlation, Bus stop	**18. Distribution Statement** No restrictions. This document is available to the public through The National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 73	**22. Price**

Form DOT F 1700.7 (8-72)

DOI: 10.31979/mti.2022.2118

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ACKNOWLEDGMENTS

The authors express their sincere thanks and gratitude to the Charlotte Area Transit System (CATS) and Charlotte Department of Transportation for their help with the data required for this project.

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Executive Summary

Increasing travel demand and mobility challenges call for sustainable transportation approaches, such as public transportation systems. Transportation planners and practitioners are interested in enhancing transit ridership and reliability to account for the increase in travel demand. However, recent statistics show a marginal decline in bus ridership. With emphasis on multimodal and transit-oriented developments, there is a need to understand transit service reliability and its influence on ridership patterns.

This research aims to analyze the relationships between transit service reliability indicators and ridership. Further, it aims to analyze the effect of road network, demographic, socioeconomic, and land-use characteristics on these relationships. The associations between bus transit service reliability and ridership, and bus transit service reliability and road, demographic, socioeconomic, and land-use characteristics at a bus stop level were examined using Pearson correlation analysis.

Three hundred and ninety-four geospatially distributed bus stops in the city of Charlotte, North Carolina were considered in this project. The research was conducted by categorizing the data using temporal factors (time of the day and day of the week), spatial indicators (direction of travel), and the type of bus stops. The on-time performance (OTP) percentage is considered as an indicator of bus transit service reliability, and ridership is expressed in terms of the average number of boarding passengers (per bus) at a bus stop.

A total of four times of the day, two days of the week, two directions of travel, and five types of bus stops were considered for the Pearson correlation analysis between bus transit service reliability indicators and ridership. The results show that ridership has a positive association with bus transit service reliability for various times of the day and days of the week. Specifically, ridership during morning-peak and night-time hours of a typical weekday are highly correlated with bus transit service reliability, emphasizing concentrated work trip patterns. At the weekend, a moderate positive correlation was observed for all times of the day.

The direction of travel was further used for examining the association between bus transit service reliability and ridership. A high positive correlation was observed for the inbound direction during morning peak hours on a typical weekday, potentially owing to work trip patterns towards the city's central business district. Similarly, a positive correlation between bus transit service reliability and ridership for the outbound direction was observed during night-time hours, potentially due to work-to-home trips.

The presence of intermodal transit services in a city influences overall transit ridership, and intermodal transit services require definite coordination in their operations for better reliability. The Pearson correlation analysis was conducted by classifying the data based on the type of bus stop to understand the influence of location parameters. The results indicate that transit centers and bus stops near LRT stations (typically categorized as high-activity bus stops) are positively correlated with ridership. A moderate positive correlation between bus transit service reliability and ridership was observed at bus stops located away from LRT stations.

Spatial analysis was conducted to capture data within the vicinity of a bus stop (0.25-mile and 0.5-mile radial buffer) to understand the effect of road, demographic, socioeconomic, and land-use characteristics on bus transit service reliability. The results show that the total number of signalized intersections is associated with bus transit service reliability within the vicinity of a bus stop. A negative correlation coefficient indicates low bus transit service reliability at bus stops that have a higher number of signalized intersections within their vicinity during weekday morning peak hours. Likewise, the total number of cul-de-sacs/dead ends within the vicinity of a bus stop has a negative correlation with bus transit service reliability during weekday evening peak hours.

The results indicate that the total road network length within the vicinity of a bus stop is negatively correlated with bus transit service reliability when analyzed at an aggregate level (all times of the day) during both the morning peak hours and midday of a weekday. This indicates that, as the total network length within the bus stop vicinity increases (a denser network), transit reliability decreases. However, bus transit reliability is positively correlated with the total road network length during weekend morning peak hours.

Population, total number of household units, and the total number of employed persons within the vicinity of a bus stop are negatively correlated with bus transit service reliability during weekday morning peak hours. Also, the total and median income within the vicinity of a bus stop are negatively correlated with bus transit service reliability during weekday morning peak hours. This indicates low transit service reliability at bus stops in more populated and high-income areas.

Land-use areas with categories such as government, heavy commercial, institutional, light commercial, medical, and office are negatively correlated with bus transit service reliability during weekday morning peak hours. This indicates low transit service reliability in high land-use development areas within the vicinity of a bus stop for the categories related to commercial/employment purposes. However, land-use areas with categories such as light industrial and single-family residential are positively correlated with bus transit service reliability during weekday morning peak hours. This may be attributed to origin (residential area) and destination (commercial/ employment area) trip patterns during morning peak hours.

Institutional and light commercial land-use areas are negatively correlated with bus transit service reliability during weekday evening peak hours. However, single-family residential land-use area is positively correlated with bus transit service reliability during the same weekday time period.

A multi-family residential land-use area is positively correlated with bus transit service reliability during morning peak hours, evening peak hours, and all times of the day of a weekend. However, heavy commercial and retail land-use areas are negatively correlated with bus transit service reliability during weekend night-time.

The heated area was also used to understand the effect of land-use developments on bus transit service reliability. Institutional and multi-family residential land-use heated areas are negatively correlated with bus transit service reliability during morning peak hours, evening peak hours, and all times of the day on weekdays. Further, for a weekday morning peak, bus transit service reliability is negatively correlated with land-use heated areas like government, heavy commercial, institutional, multi-family residential, office, and recreational within the bus stop vicinity. However, light industrial and single-family residential areas are positively correlated with bus transit service reliability during morning peak hours.

Multi-family and single-family land-use heated areas are negatively correlated with bus transit service reliability during weekday evening peak hours. This may be attributed to end trip (destination) patterns in residential areas resulting in high variations in dwell time (boarding/alighting) and travel time (evening peak congestion).

Airport land-use heated areas are negatively correlated with bus transit service reliability during evening morning peak hours and all times of the day (aggregated) of a weekend. This may be attributed to the high travel demands to the airport on weekends. However, for weekend evening peak, a retail land-use heated area is positively correlated with bus transit service reliability.

The research methodology provides an examination of the association between bus transit service reliability with ridership, road, demographic, socioeconomic, and land-use characteristics at a bus-stop level. The findings imply that bus transit service reliability has a substantial impact on ridership, and bus transit service reliability is influenced by road, demographic, socioeconomic, and land-use characteristics within the bus stop's vicinity. The methodological approach is transferable to other regions and can be adopted to identify the significant characteristics of bus transit service reliability influencing ridership. Also, it can be used to understand the role of underlying external characteristics that may influence bus transit service reliability.

Transit agencies should continue to implement customer-oriented measures of reliability and satisfaction. It is possible that the values placed on reliability and ridership may not vary only based on individual characteristics, but on regional characteristics as well. The findings of this research serve as insight for public transportation agencies to effectively utilize available resources to plan and to provide equitable services to all riders.

1. Introduction

A growing population, rapid urbanization, and rising travel demand intensify the need for public transportation systems and sustainable transportation planning. The public transportation industry in the United States is worth $80 billion (Litman, 2016). In 2019 alone, 9.9 billion trips were made using public transportation systems, accounting for approximately 34 million trips each weekday (Hughes-Cromwick et al., 2019). Despite the great demand for public transportation, transit ridership has not increased significantly in the last two decades, due to the fact that current transit systems require modernization, expanded service areas, and increased service frequency with more efficiency.

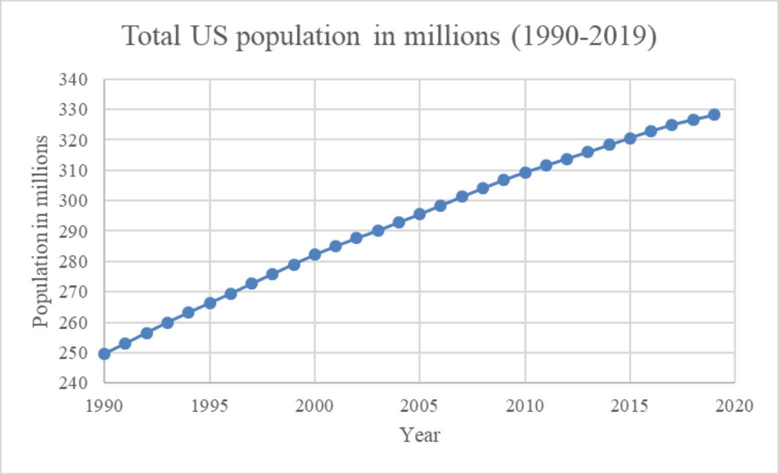
The transit ridership depends on several factors such as availability of service, frequency, transit service reliability, accessibility of bus stops, and developments ranging from manufacturing amenities, commercial centers, business parks, and the residential properties in an area. Unreliable transit services affect the commuter's trip plan and may lead to mode shift (alternate mode e.g., a car). Consequently, this may result in revenue losses to public transportation agencies and impede the sustainable transportation vision.

Public transportation plays a pivotal role in achieving sustainable transportation goals. Public transportation systems can efficiently move commuters to their destinations with fewer negative carbon impacts per person than privately owned transportation modes, such as cars (Azizalrahman and Hasyimi, 2019). Many cities in the United States are experiencing steady and significant population growth causing an increase in travel demand, and over the past few decades, there has been an increase in attention towards sustainable transportation solutions to cater to it. Figure 1 presents the population growth in the United States over the past twenty years.

Road infrastructure has not developed at the same rate as growing travel demand in many cities in the United States, mainly due to space and resource constraints. Practitioners are exploring means to increase public transportation ridership with economically efficient investment plans to meet the travel demand, reduce congestion, and contribute to sustainability. In spite of these ongoing efforts, recent statistics indicate that ridership has decreased in many cities in the United States.

The American Public Transportation Association (APTA) reports that 77% of Americans believe that public transportation is the backbone of a multi-transit lifestyle (APTA, 2020). Growing cities today are expected to have a reliable public transit system, including bus rapid transit (BRT), light rail transit (LRT), and commuter rail, which are typical public transportation systems across the United States. Several strategies are being implemented to improve these facilities, including park and ride services, intermodal services, segregated right-of-way, stations involving platforms with high-quality amenities, and intelligent transportation systems-based applications (Ishaq and Cats, 2020; Devi et al., 2021). These improvements may aid in the anticipated increase in overall ridership.

Figure 1. Population of the United States (1990–2019)



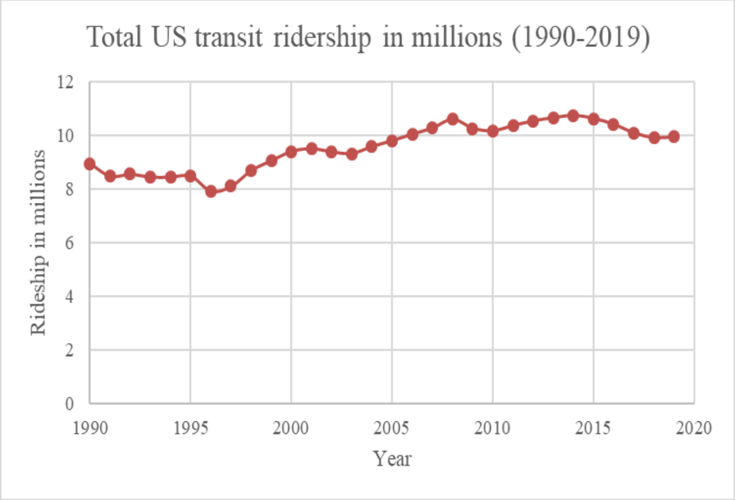
Source: U.S. Census Bureau, 2019

Public transportation use in the United States is distributed unevenly across people and places (Hernandez, 2018). Transit accounts for about 2% of all passenger miles traveled (PMT) and about 2% of overall personal trips (APTA, 2009). However, in spite of the major improvements in the public transit system, there has been no significant change in total ridership over the past 20 years. Figure 2 shows the change in ridership over the past two decades with a net increase of one million from 1990 until 2019.

This ridership trend has not reached the forecasted level, and there could be a number of reasons for this, including an increase in private car ownership, relatively low gas prices, urban sprawl, transit service laybacks, and the rise of taxi and ride services (for example, Uber and Lyft) (Graehler et al., 2019).

Transit service reliability is one of the most critical service characteristics from a transit user's perspective. While the level of service and customer satisfaction influence ridership, inconvenience (accessibility, frequency, comfort), operations uncertainty, and delayed services diminish the transit user's confidence and may ultimately result in an overall decline in ridership. Therefore, providing reliable bus transit service might foster a more significant, satisfied, and committed base of bus transit users.

Figure 2. Total Ridership in the United States (1990–2019)



Source: APTA, 2021

1.1 Need for Research and Problem Statement

Many urban areas face mobility challenges due to an increase in travel demand and resource constraints. Transportation agencies are exploring other avenues to increase public transportation ridership with economically efficient investment plans to meet the travel demand, reduce congestion, and contribute to sustainability. Despite ongoing efforts, recent statistics indicate that ridership has decreased in many cities in the United States, and bus ridership alone decreased by 5% in 2017 compared to 2016 (Driscoll et al., 2018).

There is a need to research and identify factors that encourage the use of public transportation systems over other modes of transportation. The availability of transit service, frequency of the transit service, and reliability based on transit performance are a few of the factors that affect transit ridership. The perception of bus transit service reliability among riders is based on on-time arrival/departure and waiting times. Yet, intra-city bus services often show inconsistencies in on-time arrival/departure at bus stops, possibly because buses share their travel space with other transportation modes, making them vulnerable to recurrent and non-recurrent congestion. These delays impact the riders' impression of the system.

The most commonly used measure of bus transit service reliability is on-time performance (OTP), and different OTP thresholds are used by public transportation agencies. The relationship between the OTP threshold and ridership was not explored widely in the past, and therefore, new research is needed to better understand this important relationship.

The association between bus transit service reliability and ridership at a bus stop level could vary by day of the week, time of the day, direction of travel, and the type of bus stop. The effect of bus transit service reliability on ridership could also depend on the road networks, demographics, socioeconomics, and land-use characteristics within the vicinity of a bus stop. For example, low-income groups may perceive bus transit service reliability differently than medium- or high-income groups.

This research, therefore, aims to analyze the relationship between bus transit service reliability indicators and ridership by examining the effects of road network, demographic, socioeconomic, and land-use characteristics. The findings will help public transportation agencies to effectively utilize available resources, plan, and provide equitable services to all riders.

1.2 Research Objectives

The objectives of the proposed research are:

- to research the relationship between bus transit service reliability and ridership,
- to analyze the spatial and temporal variations in bus transit service reliability over the study area, and
- to analyze the relationship between bus transit service reliability and road, demographic, and socioeconomic characteristics.

1.3 Organization of the Report

The remainder of the report is organized as follows. Chapter 2 presents a review of past studies on transit service reliability performance measures and their applicability. A detailed overview of factors affecting transit ridership and reliability is also included in the chapter. Chapter 3 outlines the methodological approach used in this research. Chapter 4 provides the discussion on the study area, data collection, and data processing. Chapter 5 summarizes the results from the Pearson correlation analysis between bus transit service reliability and ridership. Chapter 6 summarizes the results from the Pearson correlation analysis between bus transit service reliability and road network, demographic, socioeconomic, and land-use characteristics. Chapter 7 summarizes the conclusions and limitations of this research and future directions for this research.

2. Literature Review

This chapter begins with a description of relevant findings from the literature on factors influencing transit ridership, transit service reliability performance measures, and the effect of transit service reliability on ridership. The limitation of the past studies is also included here.

2.1 Factors Influencing Transit Ridership

The factors affecting public transit ridership investigated in past research studies can be classified into external and internal factors. External factors, such as fuel price, employment, and population, are not related to the transit system and its operators. Internal factors include the transit system characteristics such as transit service, quality of service, transit fares, and operating hours.

Descriptive and causal analysis are two widely adopted methodologies in evaluating the factors influencing transit ridership. The attitudes and perceptions are descriptive in nature, and system-related studies are based on causal analysis. The outcomes from the descriptive analysis are generally helpful in planning and policy decisions, while, in contrast, cause and effect outcomes may benefit travel demand-supply analysis and measurements of a transit system's performance.

Common descriptive analysis studies dealing with external factors include computer-aided surveys, on-board travel surveys, and the use of National Household Travel Survey (NHTS) data to assess public transit travel demand based on factors like population density, housing around transit stops, and the influence of advanced traveler information systems (ATIS) on transit ridership (Cervero, 1994; Abdel-Aty, 2001; Chakrabarti, 2017). Causal analysis addressing ridership from external factors' perspective, however, seeks to develop explanatory models using population and geographic characteristics, regional economy, and transportation variables. The exploratory modeling techniques adopted by a few researchers include ordinary least square (OLS) regression and two-stage least square regression (Taylor et al., 2009; Brakewood et al., 2015).

Similarly, descriptive statistics-based studies focusing on internal factors include on-board surveys of transit users' attitudes and travel behavior patterns to understand the influence of variables in the control of transit operators or agencies on transit ridership. These variables include transit fare, bus stop amenities, and transit service quality factors (Syed et al., 2000; Tirachini et al., 2010; Lai and Chen, 2011; Sharaby and Shiftan, 2012; Redman et al., 2013; Abenoza et al., 2017). Causal analysis-based studies focusing on internal factors use data from local transit authorities to assess transit-related factors such as transit service reliability (based on OTP) and transit frequency, and their influence on transit ridership (Chakrabarti and Giuliano, 2015; Gkiotsalitis and Kumar, 2018).

External factors, such as road and land-use characteristics and socioeconomic and demographic factors at a transit stop/route/network level, also influence transit ridership (Pulugurtha and Agurla, 2012; Guerra, 2014; Bhattacharjee and Goetz, 2016). Other studies that explored the influence of public transportation on land use include the development of a framework to identify ridership trends based on land-use types, such as commercial and residential, and amenities, such as transportation, education, or entertainment. Those studies showed a positive association between ridership and the amenities at the earlier stage of development, but a reduction in ridership was observed in later stages (Baum-Snow and Kahn, 2000; Putman, 2013; Hurst and West, 2014; Hu et al., 2016; Ishikawa and Tsutsumi, 2016; Li et al., 2016; Sun et al., 2016).

Studies have shown empirical evidence that socioeconomic characteristics can explain the variation in travel patterns more than land-use characteristics (Stead, 2001). A few research studies signify that the built environment—pedestrian-friendly intersections, walk and bike connectivity, safety, etc.—at transit stops influences ridership (Khattak and Rodriguez, 2005; Kim et al., 2007; Forsyth et al., 2009; Choi et al., 2012; Pulugurtha and Srirangam, 2021). A few studies also state that safety and accessibility of bus transit systems play a vital role in increasing transit system usage, which increases ridership (Pulugurtha et al., 1999; Pulugurtha and Vanapalli, 2008; Pulugurtha et al., 2011).

Past studies also documented the effect of internal factors, such as service reliability, headway, and travel times of the bus-transit service, on transit ridership (Van Oort et al., 2015; Ansari Esfeh et al., 2021). Other studies exploring the influence of internal factors, such as service time, adherence time, and operating time, on transit ridership mainly focus on developing a framework to identify ridership trends based on integrating the transit users' and operators' perspectives on transit service reliability. Those studies indicated that the improved travel and service times initially positively influenced ridership. Later, there is a trend reversal of reduction in ridership with improved service and travel time (Conway et al., 2017; Coleman et al., 2018).

Some research studies (Hickey, 1992; Ting and Schonfield, 2005; Almasi et al., 2016) explored the intermodal effect of public transportation, mainly focusing on the coordination between LRT and bus transit services and optimization strategies. These studies found that ridership of one transit service may be influenced by the operating or scheduling times of other transit services.

2.2 Transit Service Reliability Performance Measures

Public transit remains one of the most critical parts of a region's overall transportation system. It promotes sustainability, increases accessibility, and improves the mobility of various population groups (Gershon, 2005). Monitoring of the performance measures of public transportation has improved since advanced monitoring and tracking systems have been deployed by transit agencies worldwide. The performance measures related to transit service reliability are primarily focused on improving ridership, and they help transit agencies assess specific goals to improve services. The agencies use transit performance measures for service monitoring, economic performance evaluation, internal communications, development of service design standards, communication of achievements and challenges, and community benefits (Ryus, 2003).

Past research on bus and LRT ridership suggests that the frequency of service influences ridership (Brakewood et al., 2015). Similarly, factors such as mixed traffic lanes, bus lanes, median bus-ways on city streets, reserved lanes on freeways, and bus-only roads influence transit system performance (Levinson et al., 2003). A few studies identified variables such as fares, number of stations, average distance between two stations, average speed, average peak/non-peak headways, and vehicle capacity as factors influencing transit system performance (Hensher and Golob, 2008).

Bus transit service reliability has been defined in many ways, from the perspectives of both users and transit agencies. The most widely used are OTP and headway adherence (Strathman and Hopper, 1993; Nakanishi, 1997; Strathman et al., 1999; Bertini and El-Geneidy, 2003; Currie and Delbosc, 2011; Surprenant-Legault and El-Geneidy, 2011; Duddu et al., 2019; Kathuria et al., 2020). Wong and Khani (2018) proposed a methodology to develop a performance measure for transit service reliability, namely traffic delay, by estimating and isolating dwell time delay from general traffic delay using stop-level automatic vehicle location (AVL) and automated passenger count (APC) data.

In recent years, transit service reliability has been considered a critical element to quantify the service aspects of a system (Currie and Delbosc, 2011), and it has become an important topic of concern for researchers, transit operators, and users. Transit service reliability significantly affects user experience and service quality perceptions, and several factors influence it, including traffic conditions, road construction, vehicle maintenance and quality, schedule achievability, passenger demand variations, operational control strategies, weather, route length and number of stops, operator driving skills, route familiarity, and adherence to the schedule (Levinson, 2004).

According to the Transit Capacity and Quality of Service Manual (TCQSM) 3rd Edition, public transit service reliability is based on the transit user's comfort and convenience for fixed-route services (FTA, 2013). The headway adherence (time difference between successive services), OTP, and excess wait times are the standard reliability measures based on a delay due to schedule deviations. Headway adherence is measured based on headway variability, and it applies to public transit services operating with headways of 10 minutes or less (Diab et al., 2016). Transit users experience minimal or no wait time before boarding the next transit operating with headways of 10 minutes or less, and thus the headway adherence reliability measure may not be appropriate from the user's perspective for such transit services.

The OTP and excess wait time measures are applicable for services operating with headways greater than 10 minutes. The OTP is based on service deviations in actual and scheduled departure times and is defined as the percent of schedule deviations that falls in the range of 1 minute early to up to 5 minutes late. The best OTP service-level identifies on-time percentage between 95% to 100%, i.e., a transit user making one round trip per weekday with no transfers experiencing one not-on-time vehicle every two weeks. However, some transit agencies use different ranges to define OTP based on region-specific operations. Nearly 42% of agencies use a value greater than 5 minutes late for on-time, and 8% use a value greater than 5 minutes early for on-time (TCRP

2003). The excess wait time measure is based on the average of schedule deviations and overall deviation in schedule, but point-level deviations are not considered in OTP measurements. Therefore, this research adopts OTP as the measure for bus transit service reliability analysis, and it is defined as the difference between the scheduled and actual departure times at a given bus stop.

2.3 Significance of Transit Service Reliability

Some studies investigated the cost of transit quality factors such as crowding, transit frequency, and user information systems on transit service reliability (Litman, 2008). They proposed a methodology to quantify the cost of transit service reliability on transit users using automatic vehicle location (AVL) data, which is considered high-resolution transit data captured using global positioning system (GPS) (Casello et al., 2009). The findings showed that improving transit service reliability at a given stop can decrease transit users' generalized costs by 15% in a reasonably reliable network. Benezech and Coulombel (2013) studied the impact of transit frequency and reliability on travel cost and the choice of transit users' departure time.

In general, automated passenger counter (APC) systems are used to collect the transit data. Paired with AVL technology, they measure ridership and reliability. However, AVL technology is not used by all transit agencies, and acquiring this data involves privacy and legality issues. Studies that used APC data include Patnaik et al. (2004) and Wong and Khani (2018). Studies that used AVL-obtained data include Camus et al. (2005), Lin et al. (2008), and Barabino et al. (2015).

Data analysis of transit service reliability-related variables were approached differently in each study, based on the respective study's objectives. Previous research studies developed a set of multivariate regression models to estimate bus arrival times and to assist with transit users' decision-making (to reduce waiting times due to transit unreliability) at major bus stops along a route in an urban network (Patnaik et al., 2004).

Some studies focused on integrating the transit users' and transit agencies' perspectives on transit service reliability and studied the response of transit users to schedule adjustments to improve reliability (Diab et al., 2015). Delgado and Aktas (2016) explored strategies to improve transit networks' reliability resilience by incorporating technologies to withstand harsh weather conditions and upgrading tracks and bridges.

Several researchers have studied transit service reliability at stop, route, and network levels. Some studies focused on service reliability based on bus operational characteristics and performance measures such as punctuality index based on routes (PIR), deviation index based on stops (DIS), and evenness index based on stops (EIS) (Chen et al., 2009). Duddu et al. (2014; 2019) evaluated transit OTP at a bus stop level based on travel time and delay at previous bus stops. Jing et al. (2015) explored the effect of the uncertainty of a transit vehicle's arrival/departure times and transit users' transfers along a route on transit schedules at a network level. Gayah et al. (2016) estimated uncertainties of bus arrival times and passenger occupancies and developed models to predict travel times and individual bus passenger occupancies. Arhin et al. (2016) examined the factors influencing transit service reliability at a bus stop level, such as the number of passengers alighting and boarding, dwell time, and bus stop location with respect to the nearest intersection. Hu and Shalaby (2017) employed regression analysis to determine factors that influence bus reliability and speed at route and segment levels. The results obtained from this study indicated that lower transit service reliability and speed are significantly associated with an increase in service distance, signalized intersection density, stop density, volume of boarding and alighting passengers, and traffic volume.

2.4 Transit Service Reliability on Transit Ridership

The estimation of public transit ridership based on transit service reliability is a topic of great interest to practitioners and researchers. Unreliable transit services cause delays to transit users, vehicle crowding, and disrupted services, and, consequently, negatively affect ridership. This could impact the main aim of several transit agencies to attract car users to transit services.

Recent studies on public transportation stated that reliability and frequency are important public transit factors that attract car users to public transport (Redman et al., 2013). Kashfi et al. (2015) found that the ratio of in-vehicle transit travel time to in-vehicle automobile travel time has a statistically significant negative relationship with transit ridership in Brisbane, Australia. Abate et al. (2013) studied the relationship between reliability and productivity in passenger railroad services in Europe. The findings from their research indicate that increasing reliability does not harm the productivity of railway operations and aiming to improve both may be a feasible strategy.

Tyndall (2018) evaluated the New York City's Select Bus Service program and found that policy intervention resulted in increased bus service frequency and improved bus arrival reliability, and also increased bus mode share. Tang and Thakuriah (2012) evaluated the effect of real-time bus information on the Chicago Transit Authority's (CTA) overall ridership, which showed an increase due to providing real-time information to transit users.

To increase the transit demand, transit agencies focus on increasing the reliability of transit, because unreliable transit services compel transit users to invest more time in making a trip, which often results in longer wait times at transit stops. Uncertainty in planning a transit trip, especially if an en-route transfer is involved, becomes complicated for a transit user, resulting in a higher likelihood of reduced transit usage or dependency on alternate modes of transportation. As a counter-strategy, transit agencies provide transit users with real-time transit location information so the rider is better informed about possible delays and can plan their trip efficiently with lower wait times at transit stops.

2.5 Limitations of Past Research

A review of past literature provides a comprehensive overview of the data collection strategies, variables considered, and research methodologies adopted to identify the relationship between transit service reliability, ridership, and the factors influencing them. The research methodologies were adopted to estimate the association at different levels (route, city, and county). However, not much was documented on transit service reliability at a bus stop level, nor on the effect of temporal indicators (day of the week, time of the day), spatial indicators (direction of travel), and type of bus stop on the association between bus transit service reliability and ridership. Also, the effects of road network, demographic, socioeconomic, and land-use characteristics on transit service reliability at a bus stop level by time of the day and day of the week have not been explored. This research addresses these limitations.

3. Methodology

This chapter provides an overview of the methodological framework adopted in this research, which includes the following steps:

- Identifying and estimating the bus transit service reliability performance measure.
- Understanding the association between bus transit service reliability and ridership by considering temporal (time of the day and day of the week) and spatial (direction of travel) indicators.
- Examining the relationship between bus transit service reliability and ridership by the type of bus stop.
- Examining the effect of road network, demographic, socioeconomic, and land-use characteristics on bus transit service reliability within the vicinity of bus stops by the time of the day and the day of the week.

3.1 Identifying and Estimating Bus Transit Service Reliability Performance Measures

The bus transit system considered in this research has headways between services from 20 minutes up to 60 minutes for all the periods (morning peak, mid-day, evening peak, and night-time) for both weekdays and weekends. The TCQSM 3rd Edition recommends OTP percentage as a measure of reliability for all bus headways greater than 10 minutes. The Charlotte Area Transit System (CATS) monitors the OTP of the bus service at a bus stop level, and they collected the data pertaining to bus service.

In general, departure adherence is considered to be critical in calculating the serviceability of the bus transit system (Mahdavilayen et al., 2020). The data provided by CATS has actual departure time and scheduled time (or scheduled departure time) for the transit service evaluation at each bus stop along with other variables. The departure adherence is computed using Equation 3-1.

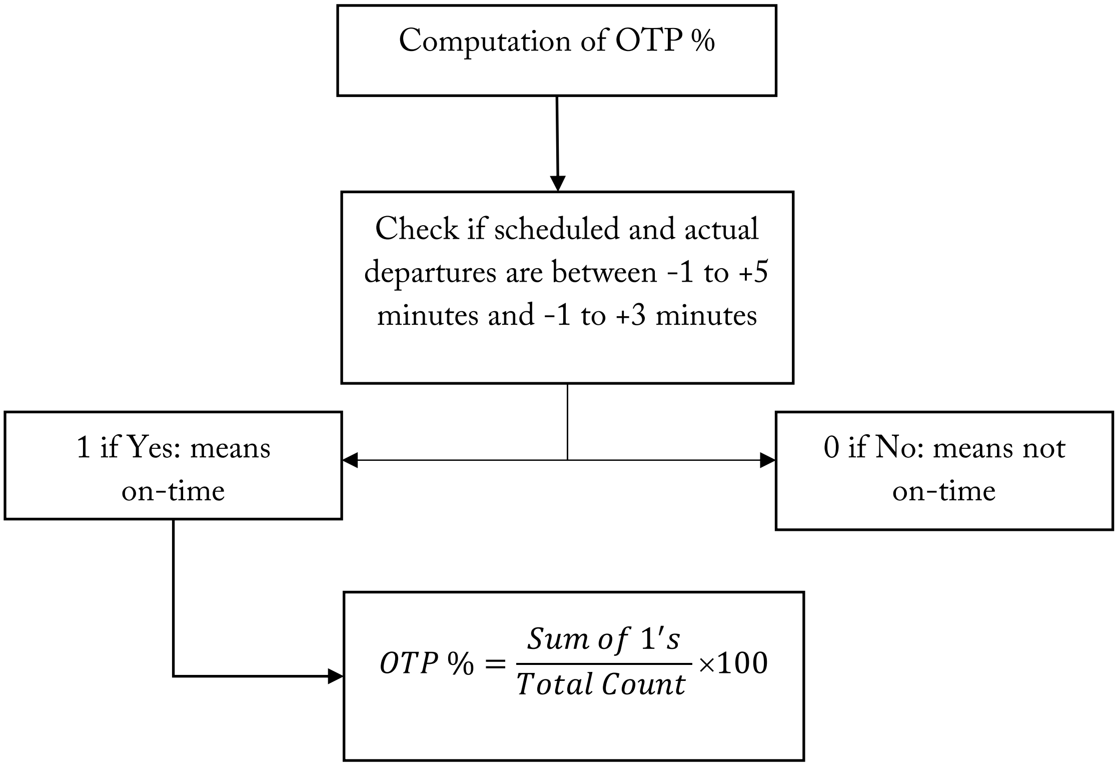
Departure Adherence = Actual Departure Time - Scheduled Departure Time (3-1)

The schedule deviation given by the actual departure time minus the scheduled departure time (per one-way trip) is considered "on-time" if the outcome lies in the range of -1 minute ("early") to +5 or +3 minutes ("late"). Beyond this range, results are considered not on-time or late and contribute to the system's unreliability.

The OTP of a bus service for a given time period is measured as a percentage of the schedule deviations in departures at a bus stop. The deviations are -1 to 5 minutes of the desired time of departure, i.e., no more than 1 minute early and up to 5 minutes late (TCQSM 3rd Edition [FTA, 2013]). For example, a bus with a scheduled departure time is 6:20 PM. The bus is said to be on-time if it departs between 6:19 PM and 6:25 PM. For passengers alighting the bus, it helps to provide adequate time to plan their arrival at their respective destinations and to better plan for any transfers during the journey.

Additionally, the percentage of schedule deviations in bus departures based on -1 to 3 minutes of the desired time of departure was also computed and evaluated in this research. With the obtained values of departure adherence, the OTP values were computed using the framework in Figure 3.

Figure 3. Framework for OTP Computation



If the computed departure adherence lies between -1 to +5 minutes and -1 to +3 minutes, then a Boolean value is assigned to it. OTP is computed based on the number of on-time trips divided by the total number of trips. As OTP is expressed in terms of percentage, it is then multiplied by 100. This OTP percentage serves as bus transit service reliability (BTR), which is computed for bus services separately by the time of the day, the day of the week, the direction of travel, and the type of bus stop. The desired values are obtained by day of the week, time of the day, and direction of travel by using Equation 3-2, where BTR stands for bus transit service reliability.

$$BTR = \frac{\#\ of\ \text{bus}{-}stop\ level\ trips\ the\ bus\ is\ on{-}time\ on\ a\ weekday\ (in\ whole\ year)}{Total\ \#\ of\ \text{bus}{-}stop\ level\ trips\ on\ a\ weekday\ (in\ whole\ year)} \times 100 \qquad (3\text{-}2)$$

Table 1 describes the bus transit service reliability ranges and their interpretation from a transit user's perspective and an operator's perspective per the TCQSM manual 3rd Edition. For example, if the computed bus transit service reliability lies within the considerable threshold of 70%–79%, the bus is said to be reliably operating during the analysis period.

Table 1. Bus Transit Service Reliability Expressed as OTP Percentages from Passenger and Operator Perspectives

On-time performance	Passenger perspective	Operator perspective (system-level)
95–100%	Passenger making one round trip per weekday, with no transfers, experiences one not-on-time service every two weeks	• Achievable by operating below capacity on a grade-separated guideway not shared with non-transit vehicles, with few infrastructure or vehicle problems
90–94%	Passenger making one round trip per weekday, with no transfers, experiences one not-on-time service every week	• Achievable by operating on a grade-separated guideway not shared with non-transit vehicles
80–89%	Passenger making one round trip per weekday, with no transfers, experiences up to two not-on-time service every week	• Typical range for commuter rail sharing track with freight rail • Typical range for LRT with some street running • Achievable by bus services in small-to mid-sized cities
70–79%	Passenger making one round trip per weekday, with no transfers, experiences up to three not-on-time service every week Passenger making one round trip per weekday, with transfers, experiences a not-on-time service every day	• Typical range for LRT with a majority of street running • Achievable by bus services in large cities
<70%	Service likely to be perceived as highly unreliable	• May be best possible result for mixed traffic operations in congested central business districts

Source: TCQSM 3rd Edition

From Table 1, 70–79% is considered achievable for large cities, i.e., a transit user making one round trip per weekday, with no transfers, experiences three not-on-time services every week. The considered study area (Charlotte) falls under the category of large city, and thus this range is considered a threshold for bus transit service reliability in this research.

It is important to note that, as specific data related to trips involving transfers are unavailable, all trips are assumed to be unlinked in this study. Bus transit service reliability computation involves the daily OTP of the transit (which means the computation of bus transit service reliability consistently mainly focuses on daily performance). Thus, the basic unit of bus transit service reliability is based on the number of days of the week present in the time period. In other words, bus transit service reliability is computed based on the combined scheduled deviations and departure times of a bus for all days of the week considered in the analysis period by considering a typical weekday or weekend. The bus transit service reliability computed for 1 minute early to 5 minutes late (-1 to +5 min.) and 1 minute early to 3 minutes late (-1 to +3 min.) are “BTR (-1 to +5 min.)” and “BTR (-1 to +3 min.).” As stated previously, the computed bus transit service reliability measures with reference to departure are expressed in percentages.

3.2 Understanding the Association between Bus Transit Service Reliability and Ridership by Considering Temporal and Spatial Indicators

A two-fold analysis was conducted to understand the relationship between bus transit service reliability and ridership and its temporal and spatial variations in the study area. Day of the week and time of the day are considered as temporal indicators, and the data are grouped accordingly. Later, the grouped data in the first step is arranged based on the direction of travel as a spatial indicator. The two steps were performed to better understand the association between bus transit service reliability and ridership.

Pearson correlation analysis was performed to examine the linear relationship between bus transit service reliability and ridership. Primarily, a typical weekday (Wednesday) and weekend (Sunday) are considered as day of the week for the entire study period (for a year) throughout the entire research. The individual 52 weeks (as the entire study period is one year) of data for the considered day of the week are collected and used for the analysis. The OTP (or BTR in this research) are computed separately for each dataset, along with the ridership values.

The next level of analysis was conducted by considering the time of the day. A total of four hours of the day were considered based on the trip’s start time (morning peak hour: 7:00 AM—9:00 AM, mid-day hour: 12:00 PM–2:00 PM, evening peak hour: 5:00 PM–7:00 PM, and night-time hour: 8:00 PM–10:00 PM). Similar datasets were prepared for the analysis by considering all of the bus services in the selected time of the day for the entire year. A total of eight datasets were formed for both the weekdays and weekends. Pearson correlation analysis was performed for the considered times of the day for that particular day of the week separately.

Inbound and outbound are the two types of travel directions present in the dataset. Pearson correlation analysis was conducted separately for both the inbound and outbound bus trips. A total of 16 datasets were developed for both the weekday and weekend, which were used for the analysis. The Pearson correlation coefficients that fell within a 95% confidence level were identified.

3.3 Understanding the Relationship between Bus Transit Service Reliability on Ridership Based on the Type of Bus Stop

The association between bus transit service reliability and ridership varies temporally for the entire study period. The considered study area in this research has LRT and bus transit as major public transportation services operating in the city. With the presence of another transit service facility nearby (in this case, LRT), it is believed that ridership of one may be affected by the other (Hickey, 1992; Ting and Schonfield, 2005; Almasi et al., 2016). Therefore, exploring the type of bus stop or type of facility existing near the vicinity of the bus transit network may add to this research. The collected data shows a variation of ridership at high-activity bus stops (bus stop located in the downtown area) compared to regular bus stops (bus stop located in the suburban area). Exploring the association between bus transit service reliability and ridership by considering the type of bus stop will also help explore the association at a granular level. The bus stops considered in this research belong to the following categories (descriptions given in Table 2).

- **LRT-related bus stops:** located withing walking distance from an LRT station.
- **Transit centers:** bus stops with high activity of transit ridership values; considered the bus stops for transfers.
- **Regular bus stops:** shows consistent ridership trends and are located far away from the LRT station.

These categories of bus stops were created by generating a 0.25-mile buffer from each LRT station, which is typically considered a standard walk distance to access a bus stop (Aultman-Hall et al., 1947; Pulugurtha and Agurla, 2012; Chakrabarti and Giuliano, 2015). The bus stops that fell within the 0.25-mile buffer are identified as LRT-related bus stops.

The processed data have transit centers operating in the local bus service routes in the urban area, and details about them were mentioned in the stop description of the bus stop. Transit centers are high activity bus stops located in the city's downtown area, which is a major stop for transferring passengers to their destinations. As these stops are located in the downtown areas, usually, high passenger activity is expected. However, the ridership pattern may not always stay high at all times of the day and days of the week. There may be high ridership activity over the weekday and a decrease in the weekend. Similarly, there may be high activity in the morning peak and low activity in the afternoon or night-time. To better understand the temporal variations pertaining to the bus stop type, the data related to the transit centers were analyzed separately.

There are regular bus stops as well as transit centers in the LRT related bus stops category. The remaining all other bus stops which are not near LRT nor a transit center were considered as regular bus stops.

Table 2. Description of the Type of Bus Stop

Type of bus stop	Description
All bus stops near LRT stations	Bus stops within a 0.25-mile buffer from each LRT station
LRT-related transit centers	Transit centers that lie within a 0.25-mile buffer generated from each LRT station
Other transit centers	Transit centers that are not near LRT stations
Other bus stops near LRT stations	All other bus stops which are not transit centers and are within a 0.25-mile buffer generated from each LRT station
All other bus stops (excluding LRT-related)	All other bus stops which are not near LRT nor a transit center

3.4 Understanding the Effect of Road Network, Demographic, Socioeconomic, and Land-use Characteristics on Bus Transit Service Reliability

To understand the effect of road characteristics on bus transit service reliability, spatial analysis using ArcGIS Pro was conducted. Buffers of a 0.25-mile and a 0.50-mile radius were generated around each bus stop. Layers pertaining to road network, demographic, socioeconomic, and land-use characteristics' data were overlaid on the generated buffers. Pearson correlation analysis was conducted between bus transit service reliability and the various characteristics within the vicinity of the bus stop by time of the day and day of the week.

Spatial analysis using ArcGIS Pro was also conducted to understand the effect of demographic and socioeconomic characteristics on BTR. As above, buffers of a 0.25-mile and a 0.50-mile radius were generated around each bus stop. Layers pertaining to demographic and socioeconomic data for 2018 at the traffic analysis zone (TAZ) level were overlaid on the generated buffers. These were intersected in ArcGIS Pro and processed to compute a proportionate area within each buffer corresponding to each bus stop ID using the pivot table tool in Microsoft Excel.

The population, number of household units, and total number of employed persons within a buffer were computed using equations 3-3 to 3-5:

$$P_i = \sum_j \frac{A_{j,i}}{A_j} \times P_j \tag{3-3}$$

where P_i is the population of the buffer "i", $A_{j,i}$ is the area of the TAZ "j" in the buffer "i", P_j is the population of the TAZ "j", and A_j is the total area of the TAZ "j".

$$HH_i = \sum_j \frac{A_{j,i}}{A_j} \times HH_j \tag{3-4}$$

where HH_i is the number of household units in the buffer "i", $A_{j,i}$ is the area of the TAZ "j" in the buffer "i", HH_j is the number of household units in the TAZ "j", and A_j is the total area of the TAZ "j".

$$E_i = \sum_j \frac{A_{j,i}}{A_j} \times E_j \tag{3-5}$$

where E_i is the number of total employed persons in the buffer "i", $A_{j,i}$ is the area of the TAZ "j" in the buffer "i", E_j is the number of total employed persons in the TAZ "j", and A_j is the total area of the TAZ "j".

Total income within a buffer was computed using equation (3-6):

$$Total\ income_i = MI_j \times \sum_j \frac{A_{j,i}}{A_j} \times HH_j \tag{3-6}$$

where MI_j is the median income of the buffer “j”, $A_{j,i}$ is the area of the TAZ “j” in the buffer “i”, HH_j is the number of household units of the TAZ “j”, and A_j is the total area of the TAZ “j”.

Median income within a buffer was computed using equation (3-7):

$$Median\ income_i = \frac{\sum(HH_j \times MI_j)}{\sum HH_j} \qquad (3\text{-}7)$$

where MI_j is the median income of the buffer “j”, HH_j is the number of household units in the TAZ “j”.

4. Study Area & Data

Below is an overview of the research's study area, data collection, data processing, and variables.

4.1 Study Area and Data Collection

The city of Charlotte, one of the most populated cities and commercial hubs in North Carolina, was chosen as the study area for this research. Located in the Piedmont region of North Carolina, Charlotte's population was ~1 million as of the 2020 census, with a growth rate of around 1.9% per annum as of 2018. CATS is the city's public transportation agency, and public transportation in the city includes buses and an LRT. This research focuses only on the bus transit system within the city limits, as shown in Figure 4.

The data for this research was obtained from CATS for the year 2017. There were 76 fixed bus transit service routes in the entire city, and of these, 49 are local bus service routes, 18 are express routes, and 9 are neighborhood routes. The city has a total of 2,933 bus stops that serve all bus service types under CATS. One-way bus fare for an adult is $2.20. The majority of the local bus routes are connected to/from the city's downtown/uptown and popular LRT stations. The city's downtown/uptown is where most of businesses are located, and most work-related trips are observed to and from the downtown/uptown area.

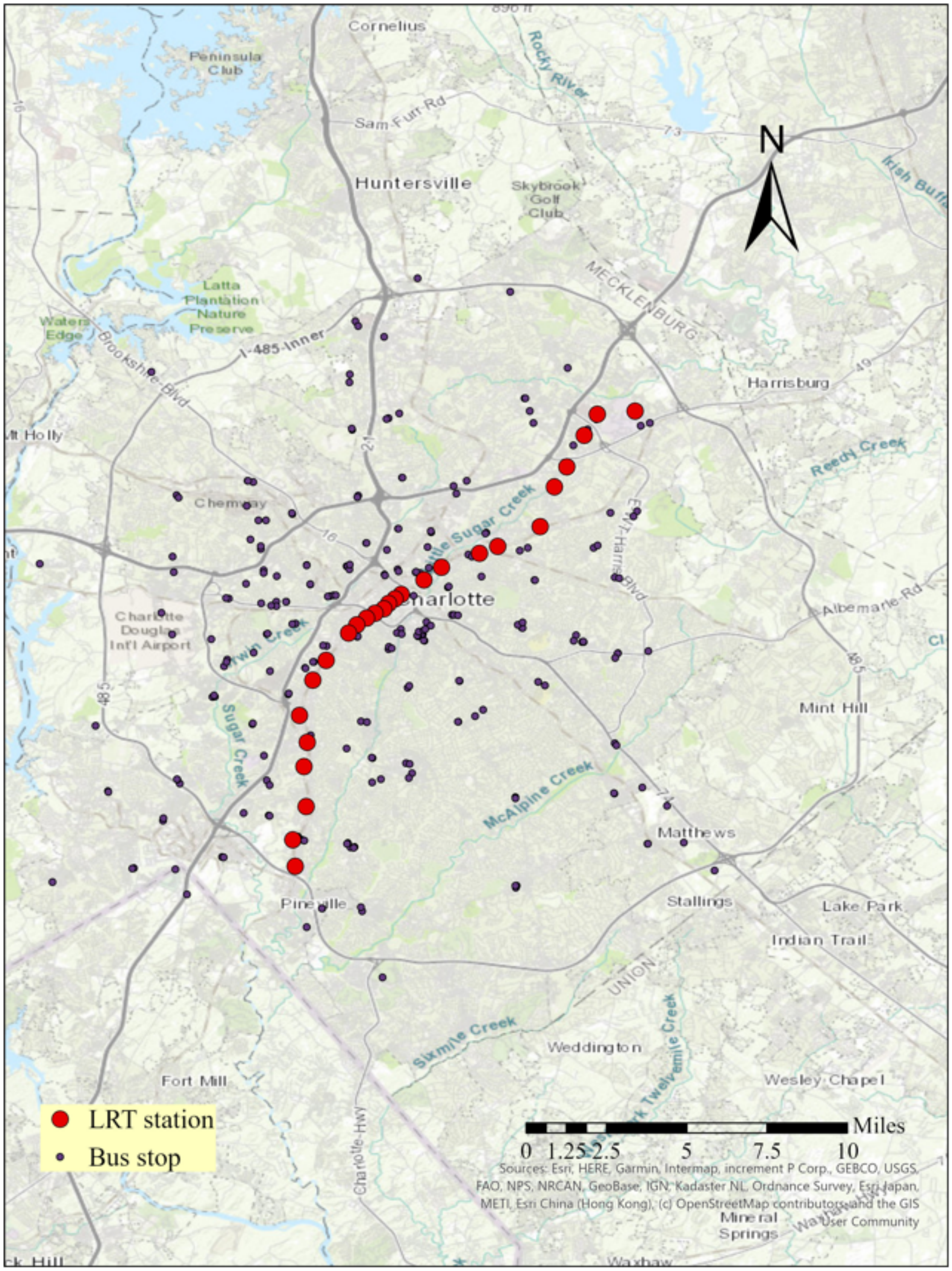
This research focuses on the 49 local bus service routes that constitute the majority of connections within the city. The express routes were not considered as they have fewer stops compared to local routes and thus decrease the number of records in both ridership and reliability data.

The transit data collected from CATS have reliability and ridership data for all of the city's bus stops (401). Of these, 394 were used here, as there was available data for all 52 weeks in the year.

4.2 Data Processing

Data was processed in two steps. The first involved identifying important bus transit service reliability and ridership details for a typical weekday and weekend. The second step involved the preparation of an integrated database by processing the data using Python Pandas. The type of bus stop was identified using ArcGIS.

Figure 4. Study Area



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

4.2.1 Bus Transit Service Reliability Data and Ridership Data

Bus transit service reliability data for a given bus stop includes actual arrival and departure time, scheduled time, direction of travel, route number, service day, stop description, date, time of the day, trip start time, and geographical coordinates.

Bus transit ridership at a given stop includes such variables as route number, direction of travel, stop description, boarding, alighting, date, trip start time, geographical coordinates, departure time, day of the week, and time of the day. The considered variables are summarized in Table 3 and 4.

Table 3. Description of Bus Transit Service Reliability Variables

S. No.	Variable	Description
1	Actual arrival time	Time point arrival in seconds past midnight (time measured from mid-night)
2	Actual departure time	Time point departure in seconds past midnight (time measured from mid-night)
3	Scheduled time	Scheduled time in seconds past midnight (time measured from mid-night)
4	Direction of travel	Direction of travel (Inbound, Outbound, North, South, East, West)
5	Route number	Different numbers for each bus route: local, express, neighborhood, & community
6	Day of the week	Weekday, Sunday, Saturday
7	Stop description	Name of the bus stop
8	Date	Date in yyyy/mm/dd format
9	Time of the day	Morning peak, mid-day, evening peak, night-time
10	Trip start time	Start time of trip with respect to 24:00:00
11	Latitude	Geographic coordinates of the bus stop
12	Longitude	Geographic coordinates of the bus stop

Table 4. Description of Bus Transit Ridership Variables

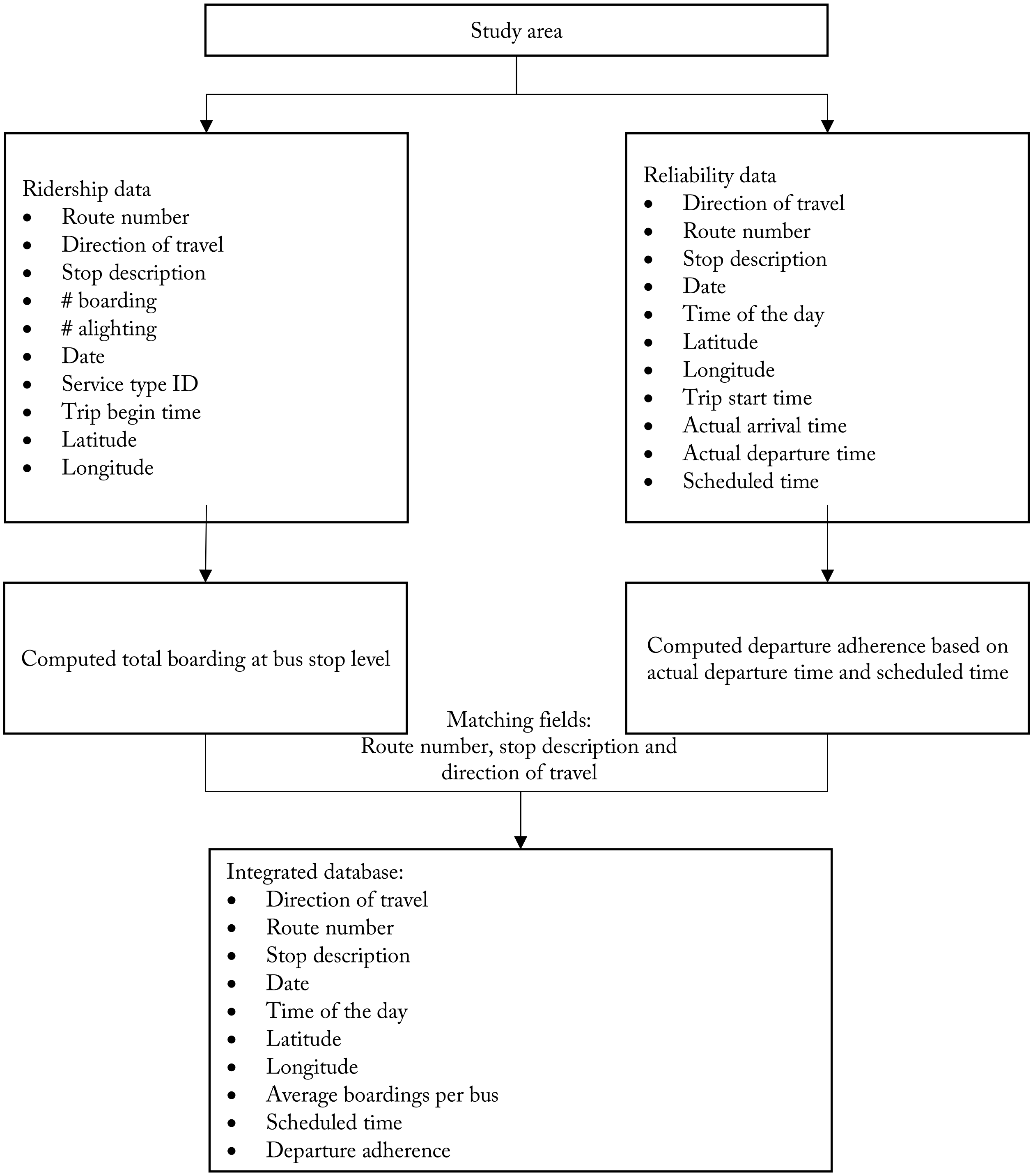
S. No.	Field	Description
1	Route number	Different numbers for each bus route: local, express, neighborhood, & community
2	Direction of travel	Inbound, Outbound, North, South, East, West
3	Stop description	Name of the bus stop
4	Boarding	Number of passengers boarding the bus
5	Alighting	Number of passengers alighting the bus
6	Date	Date in yyyy/mm/dd format
7	Trip start time	Start time of trip with respect to 24:00:00
8	Latitude	Geographic coordinates of a bus stop
9	Longitude	Geographic coordinates of a bus stop
10	Departure time	Time point departure in seconds past midnight (time measured from mid-night)
11	Day of the week	Weekday, Sunday, Saturday
12	Time of the day	Morning peak, mid-day, evening peak, night-time

4.2.2 Preparation of the Integrated Database

The bus transit service reliability and the ridership data were processed individually to identify the necessary variables for analysis. To develop an integrated database, the common and unique variables in both the bus transit service reliability and ridership data were used as matching fields: route number, direction of travel, and stop description. The process is shown in Figure 5.

The route number is a unique number assigned to each local bus route in the city limits. Similarly, the stop description is the name of the bus stop serving a local route. The direction of travel describes the direction of the trip, which can either be inbound, outbound, North, South, East, and West. The stop description and the route number are used to integrate the database because a route could have multiple bus stops. To capture the data for all of the bus stops on the route, both the route number and stop description are used as matching fields.

Figure 5. Data Integration Framework.



The integrated database consists of variables such as direction of travel, route number, stop description, date, time of the day, latitude, longitude, average number of boarding passengers per bus, average number of alighting passengers per bus, and bus transit service reliability measures (BTR [-1 to +5 min.] and BTR [-1 to +3 min.]).

As noted above, there are two directions of travel: inbound and outbound. Inbound bus stops serve trips to the City Transit Center (CTC) located in the downtown/uptown from the suburbs, and outbound bus stops serve trips from the CTC to the suburbs. North, South, East, and West bus stops serve trips to and from transit centers in specified directions of the city. The obtained database has 181 inbound bus stops, 175 outbound bus stops, 13 North-direction bus stops, 15 South-direction bus stops, 5 East-direction bus stops, and 5 West-direction bus stops. As there are no sufficient samples in the directional bus stops for a separate analysis (a total of 38 samples), they are also classified as inbound and outbound based on their reference with geographical North. If the bus is due North and leaving towards the transit center, it is considered an outbound bus stop. A similar logic was followed for the remaining directions in order to classify them as inbound and outbound bus stops for this study.

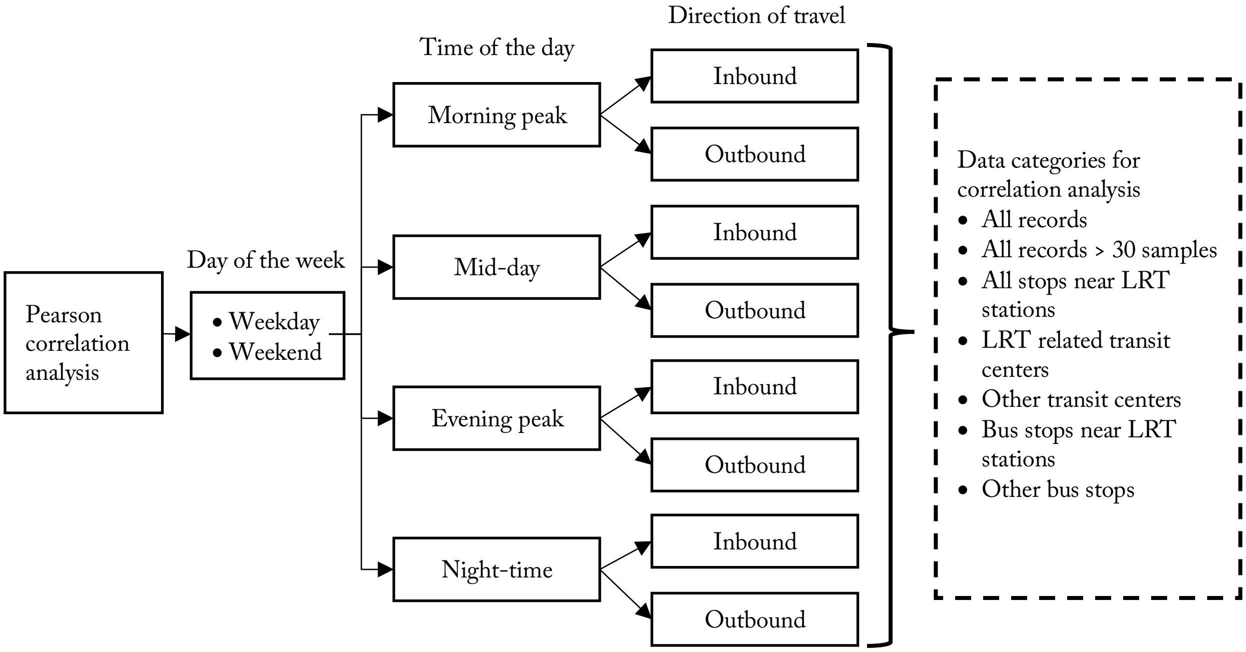
The processed data was used to compute the bus transit service reliability and ridership at the bus stop level. Actual departure time and scheduled time were used to compute departure adherence, which was used in the computation of bus transit service reliability (OTP in this research).

The final integrated database was then used for analysis, which involved arranging the data by day of the week, time of the day, direction of travel, type of bus stop, and then conducting the Pearson correlation analysis.

5. Examining the Association Between Bus Transit Service Reliability and Ridership

This chapter includes descriptive statistics of data and results from Pearson correlation analysis, which was performed to understand the association between bus transit service reliability and ridership. Further, this association is analyzed by considering spatiotemporal indicators and the type of bus stop. Figure 6 shows the classification of Pearson correlation analysis after data segregation.

Figure 6. Data Classification for Pearson Correlation Analysis



Note: The data classification for Pearson correlation analysis was performed after the data was segregated based on time of the day, day of the week and direction of travel.

Bus transit service reliability for each individual bus stop is computed based on the bus stop's frequency of service. Pearson correlation analysis was conducted in a total of five stages based on the data segregation, and a total of 182 correlation tables were developed and examined. The processed data was analyzed by segregating the data by day of the week, time of the day, direction of travel, and type of bus stop.

A typical weekday (Wednesday) and weekend (Sunday) were used for analysis by day of the week, and a total of four times of the day were considered and filtered based on the trip start time (morning peak: 7:00 AM–9:00 AM, mid-day: 12:00 PM–2:00 PM, evening peak: 5:00 PM–7:00 PM, and night-time: 8:00 PM–10:00 PM) for analysis by time of the day. Inbound and outbound are the two directions considered as spatial indicators for the analysis by the direction of travel. Inbound direction trips are from sub-urban areas to CTC, whereas outbound trips are from CTC to sub-urban areas.

The presence of intermodal transit services within a city influences its ridership. Coordination of transit's operational services (bus transit and LRT) may account for the variation of ridership. In an attempt to fill the research gap, bus stops are classified based on their ridership activity. The selected bus stops for this research are geospatially distributed over the study area.

5.1 Descriptive Statistics of the Bus Transit Service Reliability and Ridership

A descriptive analysis was conducted to identify possible outliers and anomalies in the data. The minimum, median, mean, maximum, and standard deviation of bus transit service reliability and ridership were computed and examined. Table 5 summarizes the descriptive statistics of bus transit service reliability and ridership by day of the week and time of the day.

Table 5. Descriptive Statistics of Bus Transit Service Reliability and Ridership

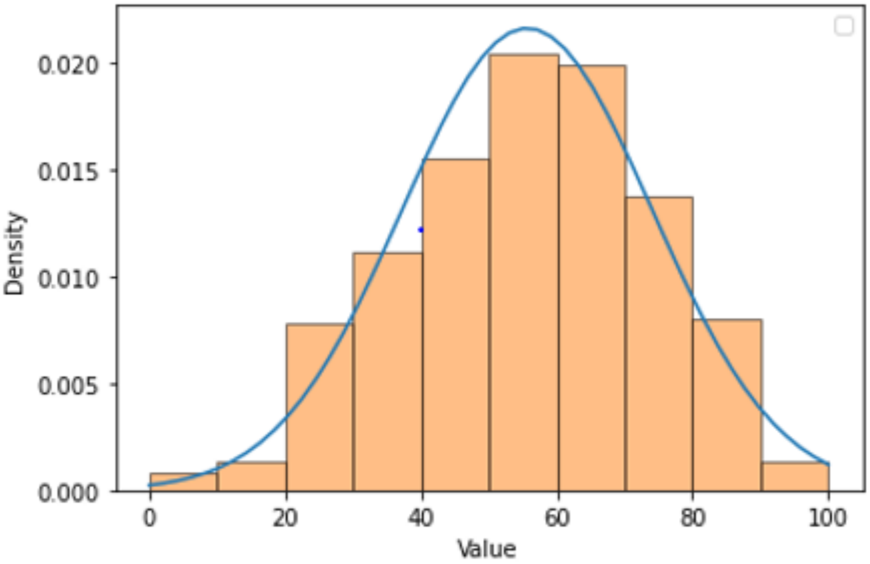
Time of the day	Variable	Minimum		Median		Mean		Maximum		Std. Dev.	
		Weekday	Weekend	Weekday	Weekend	Weekday	Weekend	Weekday	Weekend	Weekday	Weekend
All data	BTR (-1 to 5 min.)	9.84	13.07	78.70	80.82	74.70	76.32	100.00	96.97	14.93	15.19
	BTR (-1 to 3 min.)	1.60	11.57	59.44	61.16	58.34	59.57	90.38	90.91	15.12	16.18
	# of boardings (in count)	0.00	0.00	316.00	155.50	2421.56	1488.37	66992.00	33322.00	6827.68	3722.84
	Avg # of boardings	0.00	0.00	1.00	0.88	2.10	2.07	22.30	25.89	3.50	3.50
All data > 30 records	BTR (-1 to 5 min.)	9.85	13.07	78.75	80.96	74.76	76.20	100.00	96.97	14.94	15.43
	BTR (-1 to 3 min.)	1.57	11.57	59.63	61.05	58.42	59.54	90.38	90.91	15.14	16.28
	# of boardings (in count)	0.00	0.00	331.00	202.00	822.88	1564.61	3562.00	33322.00	663.60	3802.96
	Avg # of boardings	0.00	0.00	0.95	0.92	2.09	2.14	22.32	25.89	3.54	3.58
Morning peak	BTR (-1 to 5 min.)	5.94	2	77.8	86	74.13	77.84	98.99	97.93	16.95	21.60
	BTR (-1 to 3 min.)	3.9	2	56.91	66.45	56.2	63.26	94.67	96.7	17.72	21.45
	# of boardings (in count)	0	0	64	57	397.1	255.9	8998	4550	993.83	547.62
	Avg # of boardings	0	0	0.73	1	2.22	2.59	25.64	23.33	4.01	4.14
Mid-day	BTR (-1 to 5 min.)	5.62	7.89	81.91	77.55	77.33	72.89	100	96.94	17.08	18.19
	BTR (-1 to 3 min.)	3.78	5.79	62.57	55.99	61.26	55.23	95.92	94.9	18.1	19.46
	# of boardings (in count)	0	0	84	78.5	387.93	276.61	8546	4192	944.46	573.18
	Avg # of boardings	0	0	1.13	1.3	2.47	2.64	24.08	23.29	4.32	4.01
Evening peak	BTR (-1 to 5 min.)	45.44	6	80.51	76.61	76.72	72.71	93.19	97.22	13.52	15.68
	BTR (-1 to 3 min.)	30.12	6	59.35	57.15	61.01	55.16	83.75	91.61	14.79	17.39
	# of boardings (in count)	2	0	1605.5	56.5	3054.11	291.84	19475	5076	4257.44	628.06
	Avg # of boardings	0	0	1.69	0.93	2.36	2.99	12.78	33.39	2.93	5.26
Night-time	BTR (-1 to 5 min.)	3.21	20.19	82.37	77.93	77.37	73.96	97.83	99.5	16.98	16.8
	BTR (-1 to 3 min.)	1.6	7.69	62.31	56.2	60	56.32	94.63	95.54	17.33	19.3
	# of boardings (in count)	0	0	62	57	280.28	227.71	4959	3068	650.25	441.83
	Avg # of boardings	0	0	1.15	1.06	2.54	2.73	23.28	27.39	4.38	4.55

Note: BTR is bus transit service reliability.

Bus stops with greater than 30 trip records were considered for further analysis. The mean value of BTR (-1 to 5 min.) is about 74% to 76% and the mean value of BTR (-1 to 3 min.) is about 56% to 58%. This indicates that the BTR data (-1 to 3 min.) is closer to normal distribution than that of BTR data (-1 to 5 min.). Hence, the normality test was performed with BTR (-1 to 5 min.), BTR (-1 to +3 min.), and average number of boarding passengers.

A sample normal distribution diagram (for weekday morning peak hour) is shown in Figure 7. The x-axis in the histogram represents the value of the variable, while the y-axis represents the density curve. The figure shows the units that make the total area of all the bars equal to 1. The y-axis of a histogram shows how frequently the values on the x-axis occur in the data. Here, the x-axis is the value of BRT (-1 to 3 min.) and the y-axis is number of times the values of BRT (-1 to 3 min.) occur in the morning peak hour data considered for a typical weekday. The histogram plot indicates that the data is normally distributed.

Figure 7. Sample Normal Distribution Diagram for Morning Peak Hours Data for a Typical Weekday



A normality test was performed to examine whether the data is normally distributed or not. The D'Agostino's Pearson K^2 Test was conducted to determine if the data distribution departs from the normal distribution (D' Agostino, 1987; Albassam et al., 2021), and the test results in summary statistics, such as skewness and kurtosis. Skewness is a quantification of asymmetry in the distribution, whereas kurtosis quantifies whether the data is heavy-tailed or light-tailed relative to a normal distribution. The D'Agostino's Pearson K^2 test was implemented using the SciPy library in Python. The output of the test is the p-value, which is compared to the alpha value (0.05 in this case). The null hypothesis is defined as the data is normally distributed. If the p-value is greater than the alpha, then the null hypothesis is accepted. Table 6 summarizes the D'Agostino's Pearson K^2 test results for normality.

Table 6. Normality Test Results

Data classification		Variable	Weekday			Weekend		
			Statistic	P-value	Null Hypothesis	Statistic	P-value	Null Hypothesis
All data		BTR (-1 to 5 min.)	17.67	0.00	Rejected	32.09	0.00	Rejected
		BTR (-1 to 3 min.)	5.12	0.08	Accepted	9.47	0.01	Rejected
		# of boardings (in count)	36.10	0.00	Rejected	31.60	0.00	Rejected
Morning peak		BTR (-1 to 5 min.)	23.44	0.00	Rejected	44.02	0.00	Rejected
		BTR (-1 to 3 min.)	3.73	0.16	Accepted	7.85	0.17	Accepted
		# of boardings (in count)	25.81	0.00	Rejected	25.91	0.00	Rejected
Mid-day		BTR (-1 to 5 min.)	24.29	0.00	Rejected	16.11	0.00	Rejected
		BTR (-1 to 3 min.)	5.96	0.05	Accepted	3.47	0.18	Accepted
		# of boardings (in count)	44.64	0.00	Rejected	14.28	0.00	Rejected
Evening peak		BTR (-1 to 5 min.)	8.12	0.12	Accepted	14.50	0.00	Rejected
		BTR (-1 to 3 min.)	6.97	0.03	Rejected	3.76	0.15	Accepted
		# of boardings (in count)	38.67	0.00	Rejected	35.66	0.00	Rejected
Night-time		BTR (-1 to 5 min.)	16.94	0.00	Rejected	9.63	0.01	Rejected
		BTR (-1 to 3 min.)	2.75	0.25	Accepted	5.90	0.05	Accepted
		# of boardings (in count)	14.81	0.00	Rejected	17.56	0.00	Rejected
Morning peak	Inbound	BTR (-1 to 5 min.)	17.19	0.00	Rejected	31.07	0.00	Rejected
		BTR (-1 to 3 min.)	4.53	0.10	Accepted	6.74	0.03	Rejected
		# of boardings (in count)	5.17	0.08	Accepted	5.96	0.05	Accepted
	Outbound	BTR (-1 to 5 min.)	3.76	0.15	Accepted	16.28	0.00	Rejected
		BTR (-1 to 3 min.)	0.68	0.71	Accepted	3.19	0.20	Accepted
		# of boardings (in count)	71.56	0.00	Rejected	23.11	0.00	Rejected
Mid-day	Inbound	BTR (-1 to 5 min.)	24.30	0.00	Rejected	10.93	0.00	Rejected
		BTR (-1 to 3 min.)	8.76	0.59	Accepted	4.90	0.09	Accepted
		# of boardings (in count)	15.72	0.00	Rejected	2.84	0.24	Accepted
	Outbound	BTR (-1 to 5 min.)	11.19	0.00	Rejected	6.67	0.04	Rejected
		BTR (-1 to 3 min.)	2.55	0.28	Accepted	0.22	0.90	Accepted
		# of boardings (in count)	41.99	0.00	Rejected	29.25	0.00	Rejected
Evening peak	Inbound	BTR (-1 to 5 min.)	8.13	0.02	Rejected	22.34	0.00	Rejected
		BTR (-1 to 3 min.)	4.52	0.10	Accepted	3.85	0.15	Accepted
		# of boardings (in count)	4.98	0.08	Accepted	63.40	0.00	Rejected
	Outbound	BTR (-1 to 5 min.)	4.68	0.10	Accepted	3.69	0.16	Accepted
		BTR (-1 to 3 min.)	3.61	0.16	Accepted	1.11	0.57	Accepted
		# of boardings (in count)	70.19	0.00	Rejected	40.24	0.00	Rejected
Night-time	Inbound	BTR (-1 to 5 min.)	14.83	0.00	Rejected	8.68	0.01	Rejected
		BTR (-1 to 3 min.)	3.83	0.15	Accepted	15.00	0.00	Rejected
		# of boardings (in count)	0.14	0.93	Accepted	27.62	0.00	Rejected
	Outbound	BTR (-1 to 5 min.)	10.41	0.01	Rejected	2.71	0.26	Accepted
		BTR (-1 to 3 min.)	2.24	0.33	Accepted	0.51	0.77	Accepted
		# of boardings (in count)	31.79	0.00	Rejected	27.52	0.00	Rejected

Note: BTR is bus transit service reliability.

5.2 Examining the Association Between Bus Transit Service Reliability and Ridership

To examine the association between bus transit service reliability and ridership, the data is arranged based on the computed bus transit service reliability and its corresponding ridership for all bus stops. Table 7 summarizes bus transit service reliability and ridership at ten selected bus stops.

The correlation coefficients, which are significant at a 95% confidence level, are used in the analysis. Bus stops with greater than or equal to 30 trip records were used in the Pearson correlation analysis because a minimum sample size of at least 30 is required for validity and for statistically significant interpretations. In other words, datasets which are segregated based on the day of the week, time of the day, direction of travel, and type of bus stop with at least 30 trip records are used to perform Pearson correlation analysis.

Table 7. Bus Transit Service Reliability and Ridership at Selected Bus Stops

S. No.	Transit bus-service	BTR (-1 to 5 min.)	BTR (-1 to 3 min.)	Avg # of boarding passengers per bus
1	10_Inbound_New Renaissance Way & Burnette Ave	88.29	75.82	2.00
2	10_Inbound_Transit Center_4th & Brevard	9.85	7.80	0.01
3	10_Inbound_West Blvd & Camden Rd	90.05	79.88	0.52
4	10_Inbound_West Blvd & Remount Rd	90.12	77.01	1.68
5	10_Outbound_East Blvd & Camden Rd	72.86	30.12	2.25
6	10_Outbound_New Renaissance Way & Burnette Ave	68.02	53.00	0.00
7	10_Outbound_Transit Center_Bay G	86.87	58.30	11.12
8	10_Outbound_West Blvd & Remount Rd	81.52	54.98	0.44
9	11_Inbound_Amtrak Station	69.44	29.17	3.80
10	11_Inbound_Transit Center_Bay A	56.32	41.54	0.09

Note: BTR is bus transit service reliability.

5.2.1 Association Between Bus Transit Service Reliability and Ridership considering Temporal and Spatial Indicators

Pearson correlation coefficients were first computed by the day of the week to understand the effect of bus transit service reliability on ridership for a typical weekday and weekend. The results are summarized in Table 8.

Table 8. Association between Bus Transit Service Reliability and Ridership by Day of the Week

Day of the week	BTR (-1 to 5 min.)	BTR (-1 to 3 min.)
Weekday	0.30	0.23
Weekend	0.27	0.23

Note 1: BTR is bus transit service reliability.

Table 8 shows that a low positive correlation exists between the average number of boarding passengers per bus and bus transit service reliability based on BTR (-1 to 5 min.) and BTR (-1 to 3 min.) on weekdays and weekends. This indicates that an increase in bus transit service reliability increases ridership; transit users boarding a bus will increase as long as a bus departs on time.

From the descriptive analysis, ridership varied by the day of the week and the time of the day. Performing a correlation analysis that considers the time of the day may help clarify the association between bus transit service reliability and ridership at a more granular level, and therefore, the data was further filtered by the time of the day.

Table 9 shows a moderately positive correlation between bus transit service reliability and the average number of boarding passengers per bus during the morning peak and night-time hours on a weekday. A low positive correlation was observed for mid-day and evening peak hours.

For the weekend, the correlation remains moderately positive for all of the selected hours of the day. This change in the association between bus transit service reliability and ridership can be attributed to various types of trips (recreational and shopping trips) over the weekend (as these trips are not time defined, the same correlation exists for all selected hours of the day). The Pearson correlation analysis based on time of the day and day of the week indicates a statistically significant relationship between bus transit service reliability and ridership at a 95% confidence level.

Table 9. Association between Bus Transit Service Reliability and Ridership by Day of the Week and Time of the Day

Day of the week	Time of the day	BTR (-1 to 5 min.)	BTR (-1 to 3 min.)
Weekday	Morning peak	0.31	0.26
	Mid-day	0.29	0.2
	Evening peak	0.30	0.18
	Night-time	0.31	0.24
Weekend	Morning peak	0.33	0.30
	Mid-day	0.39	0.35
	Evening peak	0.31	0.25
	Night-time	0.32	0.27

Note 1: BTR is bus transit service reliability.

Table 10 shows the correlation analysis results for data segregated based on day of the week, time of the day, and the direction of travel, and it shows that the correlation is stronger in the inbound direction during the morning peak, mid-day, and night-time hours than the analysis conducted based on day of the week and time of the day (moderately positive to high positive). This may be due to the increased transit demand during a weekday regular-operating work hour, which results in more inbound trips when the bus service is reliable. In addition, commercial and office land-use developments, such as business parks and technological hubs, are concentrated near the central business district, resulting in an increased transit ridership during morning and evening peak hours. Transit ridership in an inbound direction is significant during morning peak and night-time hours due to the work-based trip patterns.

The average number of boarding passengers per bus is consistently, moderately, and positively correlated with bus transit service reliability based on BTR (-1 to +5 min.) and BTR (-1 to +3 min.) on a typical weekend, potentially due to recreational trip patterns. Overall, the results show a significant positive correlation between bus transit service reliability and ridership for all the times of the day and days of the week.

Table 10. Association between Bus Transit Service Reliability and Ridership by Day of the Week, Time of the Day, and Direction of Travel

Day of the week	Time of the day	Direction of travel	BTR (-1 to 5 min.)	BTR (-1 to 3 min.)
Weekday	Morning Peak	Inbound	0.57	0.56
		Outbound	0.35	0.31
	Mid-day	Inbound	0.52	0.46
		Outbound	0.36	0.26
	Evening Peak	Inbound	0.50	0.43
		Outbound	0.45	0.32
	Night-time	Inbound	0.53	0.48
		Outbound	0.37	0.31
Weekend	Morning Peak	Inbound	0.52	0.39
		Outbound	0.35	0.34
	Mid-day	Inbound	0.46	0.3
		Outbound	0.48	0.49
	Evening Peak	Inbound	0.38	0.29
		Outbound	0.37	0.33
	Night-time	Inbound	0.39	0.31
		Outbound	0.41	0.37

Note 1: BTR is bus transit service reliability.

5.2.2 Association Between Bus Transit Service Reliability and Ridership based on the Type of Bus Stop

The correlation results considering the temporal analysis indicated a statistically significant relationship between bus transit service reliability and ridership. Table 11 shows the Pearson correlation analysis results for data segregated based on day of the week and the type of bus stop.

All of the bus stops near the LRT have high ridership activity. Transit centers in each dataset are generally less in number (on average, 45–50 in each dataset). When segregated as LRT-related and not (other transit centers), the sample size is less than 30 for other transit centers. Hence, other transit centers are not analyzed separately. Primarily, the analysis was conducted by considering each type of bus stop based on the day of the week.

Table 11 reveals a high positive correlation between bus transit service reliability and ridership at all bus stops located near LRT stations. This is due to the increased ridership activity near the LRT stations. The bus stops near these stations act as feeder bus stops that result in increased ridership. A moderate positive correlation exists between the other bus stops and reliability measures considered in this research. The other bus stops located farther away from LRT stations generally have similar bus stop characteristics, and thus, the correlation values for other bus stops did not change notably.

Table 11. Association between Bus Transit Service Reliability and Ridership based on Day of the Week and the Type of Bus Stop

Day of the week	Type of bus stop	BTR (-1 to 5 min.)	BTR (-1 to 3 min.)
Weekday	All bus stops near LRT Stations	0.54	0.44
	LRT related transit centers	0.79	0.75
	Bus stops near LRT stations	0.53	0.48
	Other bus stops	0.37	0.37
Weekend	All bus stops near LRT Stations	0.51	0.46
	LRT related transit centers	0.79	0.78
	Bus stops near LRT stations		
	Other bus stops	0.31	0.26

Note 1: BTR is bus transit service reliability.

Note 2: Blank cells indicate that the correlation coefficient is not significant at a 95% confidence level.

Further, a Pearson correlation analysis was performed considering four selected hours of the day. Table 12 shows the results of this analysis for data segregated by the day of the week, time of the day, and the type of bus stop, and reveals a high positive correlation between bus transit service reliability and ridership for the bus stops near LRT stations in all the selected hours of the day. On a typical weekday, high positive correlation was observed, potentially due to consistent work trips and high ridership at bus stops near LRT stations. These bus stops serve as feeder routes to the LRT. The bus transit and LRT services may operate in coordination, which requires accurate bus transit service reliability.

Table 12. Association between Bus Transit Service Reliability and Ridership by Day of the Week, Time of the Day, and the Type of Bus Stop

Day of the week	Time of the day	Type of bus stop	BTR (-1 to 5 min.)	BTR (-1 to 3 min.)
Weekday	Morning peak	All bus stops near LRT stations	0.54	0.46
		LRT related transit centers	0.73	0.69
		Bus stops near LRT stations	0.50	0.40
		Other bus stops	0.44	0.47
	Mid-day	All bus stops near LRT stations	0.58	0.47
		LRT related transit centers	0.79	0.75
		Bus stops near LRT stations	0.59	0.53
		Other bus stops	0.42	0.36
	Evening peak	All bus stops near LRT stations	0.56	0.45
		LRT related transit centers	0.79	0.75
		Bus stops near LRT stations	0.56	0.51
		Other bus stops	0.29	0.17
	Night-time	All bus stops near LRT stations	0.59	0.48
		LRT related transit centers	0.79	0.75
		Bus stops near LRT stations	0.58	0.49
		Other bus stops	0.43	0.41
Weekend	Morning peak	All bus stops near LRT stations	0.53	0.50
		LRT related transit centers	0.74	0.72
		Other bus stops	0.37	0.30
	Mid-day	All bus stops near LRT stations	0.63	0.59
		LRT related transit centers	0.82	0.80
		Other bus stops	0.36	
	Evening peak	All bus stops near LRT stations	0.44	0.37
		LRT related transit centers	0.65	0.60
		Other bus stops	0.27	
	Night-time	All bus stops near LRT stations	0.48	0.40
		LRT related transit centers	0.69	0.62
		Other bus stops	0.27	

Note 1: BTR is bus transit service reliability.

Note 2: Blank cells indicate that the correlation coefficient is not significant at a 95% confidence level.

Transit centers near the LRT serve as large scale transfer points. The results indicate moderate to high positive correlation between bus transit service reliability and ridership for all the times of the day and days of the week. In the case of other bus stops near LRT stations, a low to moderate positive correlation was observed between the bus transit service reliability and ridership for all the times of the day and days of the week. Bus stops located away from the LRT stations may not have exclusive coordination with the LRT, and passengers who tend to board a bus at other bus stops may not be associated with the LRT.

Table 13 indicates a high positive correlation between bus transit service reliability and ridership for bus stops near LRT stations on a typical weekday, potentially due to transit user trip patterns (trips generated to/from LRT stations). Such patterns were not observed in the Pearson correlation analysis in the prior section (Table 12) where the direction of travel was not considered.

Table 13. Association between Bus Transit Service Reliability by Day of the Week, Time of the Day, Direction of Travel, and the Type of Bus Stop

Day of the week	Time of the day	Type of bus stop	Direction of travel	BTR (-1 to 5 min.)	BTR (-1 to 3 min.)
Weekday	Morning peak	All bus stops near LRT stations	Inbound	0.66	0.62
			Outbound	0.52	0.45
		Bus stops near LRT stations	Inbound		
			Outbound	0.70	0.60
		Other bus stops	Inbound	0.45	0.47
			Outbound		
	Mid-day	All bus stops near LRT stations	Inbound	0.72	0.7
			Outbound	0.51	
		Bus stops near LRT stations	Inbound	0.68	
			Outbound	0.67	0.65
		Other bus stops	Inbound		
			Outbound	0.35	
	Evening peak	All bus stops near LRT stations	Inbound	0.71	0.69
			Outbound	0.46	
		Bus stops near LRT stations	Inbound	0.67	
			Outbound	0.67	0.63
		Other bus stops	Inbound	0.27	
			Outbound		
	Night-time	All bus stops near LRT stations	Inbound	0.71	0.69
			Outbound	0.51	
		Bus stops near LRT stations	Inbound	0.67	
			Outbound	0.69	
		Other bus stops	Inbound		
			Outbound		
Weekend	Morning peak	All bus stops near LRT stations	Inbound	0.52	
			Outbound		
		Other bus stops stations	Inbound		
			Outbound		
	Mid-day	All bus stops near LRT stations	Inbound	0.50	
			Outbound	0.55	0.52
		Other bus stops stations	Inbound		
			Outbound		
	Evening peak	All bus stops near LRT stations	Inbound	0.60	0.56
			Outbound		
		Other bus stops stations	Inbound		
			Outbound	0.36	
	Night-time	All bus stops near LRT stations	Inbound	0.59	0.47
			Outbound		
		Other bus stops stations	Inbound		
			Outbound		

Note 1: BTR is bus transit service reliability.

Note 2: Blank cells indicate that the correlation coefficient is not significant at a 95% confidence level.

5.3 Discussion

The TCQSM 3rd Edition recommends using the OTP percentage as a measure of bus transit service reliability. The OTP percentage deviations proposed in the manual are -1 to 5 minutes of the desired time of departure, i.e., no more than 1 minute early and up to 5 minutes late (TCQSM 3rd Edition). However, this research included a computation that lies between 1 minute early and 3 minutes late, BRT (-1 to 3 min.), because the median of OTP percentage lies between 54% to 58%. This shows that the data is more normally distributed and performing the correlation results with a lesser threshold value (the value of BRT [-1 to +3 min.] is less than BRT [-1 to 5 min.]) can also give significant results. The obtained results show that BRT (-1 to +3 min.) is useful in examining the association between bus transit service reliability and ridership. Based on the normality test results, the null hypothesis is rejected in a few cases for both BRT (-1 to +5 min.) and BRT (-1 to +3 min.). This may be due to the sensitivity of data to the outliers, and also the presence of high variations in data (variation in bus transit service reliability values and ridership values from one stop to another). Thus, it is important to examine the variations in the data segregated by day of the week, time of the day, direction of travel, and type of bus stop. Doing so yielded correlation patterns pertaining to the bus transit service reliability and ridership. The Pearson correlation coefficients (absolute values) are higher when the data is examined at a granular level, and a positive correlation was observed when the data was sorted by the day of the week. The Pearson correlation coefficient values were almost the same for both a weekday and the weekend. When four different times of the day were considered, the correlation coefficient values were marginally higher from the previous scenario. Moderately higher correlation values were observed for the morning peak and night-time hours of both weekdays and weekends. When the direction of travel was considered, a high positive correlation was observed for the inbound direction during all selected hours of the day, for both weekdays and weekends.

Due to the variation in the ridership at different bus stops, the type of bus stop was also considered in the analysis, and a high positive correlation was observed for both inbound and outbound travel directions for bus stops near LRT stations due to high ridership activity. A moderate positive correlation was observed for other bus stops on a typical weekday during morning, mid-day, and evening peak hours. However, no significant correlation was observed on a weekend due to inconsistent ridership patterns for each type of bus stop.

6. Examining the Association between Bus Transit Service Reliability & Road, Demographic, Socioeconomic & Land-use Characteristics

This chapter includes the examination of the association between bus transit service reliability and road, demographic, socioeconomic, and land-use characteristics within the vicinity of a bus stop using Pearson correlation analysis.

6.1 Association Between Bus Transit Service Reliability and Road Characteristics

Buffers of a 0.25-mile and a 0.50-mile radius were generated around each bus stop. Layers pertaining to intersection data were then overlaid on the generated buffers. The overlaid layers were intersected using the "intersect" feature in ArcGIS Pro. The number of intersections data were further classified as sign controlled, signalized, and cul-de-sacs/dead ends.

Road characteristics around each bus stop, including details such as divided/undivided, number of lanes, speed limit, presence of median, and total network length within a buffer, were captured using a 100 ft buffer. For some bus stops, the street network was not intersected within a 100 ft buffer, but instead, was captured manually using Google Earth and Google Maps for the year 2017.

Table 14 shows the Pearson correlation analysis results for the association between bus transit service reliability by day of the week, time of the day, and the number of intersections within the bus stop vicinity of the 0.25-mile and 0.50-mile radial buffers. Bus transit service reliability has a statistically significant negative correlation with the number of signalized intersections during the morning peak hours of a weekday. This indicates low bus transit service reliability at bus stops that have a higher number of signalized intersections within their vicinity during morning peak hours. Likewise, bus transit service reliability has a statistically significant negative correlation with the number of cul-de-sacs/dead ends in the evening peak hours of a weekday. This may be attributed to work-related trip patterns (end trip to destination) during evening peak hours. However, for the morning peak hours, bus transit service reliability has a statistically significant positive correlation with the number of cul-de-sacs/dead ends within the bus stop vicinity. This indicates that bus transit service reliability is higher when the number of cul-de-sacs/dead ends are located within a bus stop's vicinity during morning peak hours, or, in other words, when the number of signalized intersections is less. For mid-day, bus transit service reliability has a statistically significant negative correlation with the total number of intersections within the bus stop vicinity for a weekday. This indicates that bus transit service reliability decreases as the total number of intersections increases during mid-day on weekdays. For a weekend, there is a statistically significant positive correlation with the total number of intersections and sign control intersections in morning peak hours. Likewise, bus transit service reliability also has a statistically significant positive correlation with cul-de-sacs/dead ends during weekend night-time.

Table 14. Association between Bus Transit Service Reliability by Day of the Week, Time of the Day, and the Number of Intersections within the Bus stop Vicinity

Day of the week	Time of the day	# of intersections	0.25-mile buffer		0.50-mile buffer	
			BTR (-1 to 5 min.)	BTR (-1 to 3 min.)	BTR (-1 to 5 min.)	BTR (-1 to 3 min.)
Weekday	Morning peak	Signalized	-0.12	-0.12	-0.14	-0.13
		Cul-de-sac/ dead end			0.11	0.15
	Mid-day	All intersections				-0.12
	Evening peak	Cul-de-sac/ dead end		-0.11		-0.12
Weekend	Morning peak	Sign controlled			0.15	
		All intersections			0.15	
	Mid-day	Cul-de-sac/ dead end		0.14		
	Night-time	Cul-de-sac/ dead end	0.15	0.18		0.15

Note 1: BTR is bus transit service reliability.

Note 2: Blank cells indicate that the correlation coefficient is not significant at a 95% confidence level.

Table 15 shows the Pearson correlation analysis results for the association between bus transit service reliability by day of the week, time of the day, and total road network length within the bus stop vicinity of 0.25-mile and 0.50-mile radial buffers. Bus transit service reliability has a statistically significant negative correlation with the total road network length when analyzed at an aggregate level (all times of the day) on a weekday. Likewise, there is a statistically significant negative correlation with the total road network length during morning peak and mid-day hours. This indicates that bus transit service reliability decreases as the total network length within the bus stop vicinity increases (a denser network), which may be attributed to the high variation in travel time in a denser network. During the weekend, bus transit service reliability has a statistically significant positive correlation with total road network length in morning peak hours. This indicates high reliability at bus stops that have higher network length within their vicinity during morning peak hours, which may be attributed to fewer weekend trips during the morning hours compared to weekdays, and a higher service frequency at bus stops located in a denser network.

Table 15. Association between Bus Transit Service Reliability by Day of the Week, Time of the Day, and Road Network Length

Day of the week	Time of the day	Variable	0.25-mile buffer		0.50-mile buffer	
			BTR (-1 to 5 min.)	BTR (-1 to 3 min.)	BTR (-1 to 5 min.)	BTR (-1 to 3 min.)
Weekday	All	Network length		-0.13		-0.11
	Morning peak	Network length				-0.1
	Mid-day	Network length		-0.11		-0.12
Weekend	Morning peak	Network length	0.13			

Note 1: BTR is bus transit service reliability.

Note 2: Blank cells indicate that the correlation coefficient is not significant at a 95% confidence level.

Table 16 shows the Pearson correlation analysis results for the association between bus transit service reliability by day of the week, time of the day, and road characteristics at bus stop location. Point Biserial correlation, a special case of Pearson correlation for variables between nominal scale (here, BTR) and dichotomous outcome (divided/undivided and the presence of a median) was conducted. Bus transit service reliability does not have a statistically significant correlation with the divided/undivided road, speed limit, number of lanes, and presence of a median for a weekday. However, for weekend morning peak hours, there is a statistically significant positive correlation with divided/undivided road and the presence of a median, indicating high bus transit service reliability on divided roads and with a median near bus stops. Further, bus transit service reliability has a statistically significant negative correlation with the number of lanes when analyzed at an aggregate level (all times of the day) and mid-day of a weekend, indicating that bus transit service reliability decreases with an increase in the number of lanes. This may be attributed to high traffic volume and travel time variations at links with higher number of lanes.

Table 16. Association between Bus Transit Service Reliability by Day of the Week, Time of the Day, and Road Characteristics within the Bus stop Vicinity

Day of the week	Time of the day	Variable	BTR (-1 to 5 min.)	BTR (-1 to 3 min.)
Weekend	All	# of lanes		-0.15
	Morning peak	Divided	0.15	
		Median	0.16	
	Mid-day	# of lanes		-0.13

Note 1: BTR is bus transit service reliability.

Note 2: Blank cells indicate that the correlation coefficient is not significant at a 95% confidence level.

6.2 Association Between Bus Transit Service Reliability and Demographic and Socioeconomic Characteristics

Table 17 shows the Pearson correlation analysis results for the association between bus transit service reliability by day of the week, time of the day, and demographic and socioeconomic variables within a bus stop's vicinity. Bus transit service reliability has a statistically significant negative correlation with population when analyzed at an aggregate level (all times of the day), and during weekday morning peak hours. This indicates that bus transit service reliability decreases as the population near a bus stop increases. This may be attributed to the high variation in dwell time (boarding/alighting) at bus stops that serve more people. Similar results were observed for the association between bus transit service reliability and the number of household units. Further, bus transit service reliability has a statistically significant negative correlation with the total number of employed persons during weekday morning peak hours, indicating low bus transit service reliability in areas serving a higher number of employed persons during morning peak hours.

Table 17. Association between Bus Transit Service Reliability by Day of the Week, Time of the Day, and Demographic and Socioeconomic Characteristics

Day of the week	Time of the day	Variable	0.25-mile buffer		0.50-mile buffer	
			BTR (-1 to 5 min.)	BTR (-1 to 3 min.)	BTR (-1 to 5 min.)	BTR (-1 to 3 min.)
Weekday	All	Population	-0.11			-0.1
		# of households	-0.12	-0.12		-0.14
		Total income	-0.29	-0.27	-0.19	-0.23
		Median income		-0.17		-0.16
	Morning peak	Population	-0.13		-0.11	-0.11
		# of households			-0.14	-0.14
		Employment				-0.11
		Total income	-0.23	-0.21	-0.19	-0.19
		Median income	-0.14	-0.18	-0.15	-0.19
	Mid-day	Total income		-0.14		-0.13
	Evening peak	Total income	-0.2	-0.18	-0.11	-0.16
Weekend	All	# of households	0.14			
		Total income	0.13			
	Morning peak	Population	0.16			
		# of households	0.21	0.17		
		Total income	0.18			

Note 1: BTR is bus transit service reliability.

Note 2: Blank cells indicate that the correlation coefficient is not significant at a 95% confidence level.

Bus transit service reliability has a statistically significant negative correlation with the total income within bus stop vicinity when analyzed at an aggregate level (all times of the day) during weekday morning peak, mid-day, and evening peak hours, suggesting low bus transit service reliability at bus stops located in high total income areas. Likewise, bus transit service reliability has a statistically significant negative correlation with the median income within bus stop vicinity when analyzed at an aggregate level (all times of the day) and during weekday morning peak hours. Based on the correlation results, bus transit service reliability is low at bus stops located in high-income areas, which may be attributable to low ridership in these areas. The bus drivers, seeing no demand, may not be stopping at the stops in these areas and, thus, may be departing before the schedule time.

For a weekend, bus transit service reliability has a statistically significant positive correlation with population and the number of household units during morning peak hours, indicating high bus transit service reliability at bus stops that have a higher population or number of household units within its vicinity during morning peak hours. This may be attributed to smoother traffic conditions (low variation in travel times) on weekend morning peak hours compared to weekdays.

6.3 Association Between Bus Transit Service Reliability and Land-use Characteristics

Parcel level land-use development data available in geospatial format (shapefile) were used for this analysis, and ArcGIS Pro software was used to examine and extract the land-use development data. A quality check was conducted, and duplicate parcel data were removed from the dataset. The raw dataset consisted of 95 distinct land-use categories, such as the number of units, built year, land-use type, area and heated area (in square feet). The land-use developments were reclassified into 18 categories (Table 18). The land-use developments until the built year 2017 were considered. Buffers of a 0.25-mile and a 0.50-mile radius were generated around each bus stop using the "buffer" feature in ArcGIS Pro. The shapefile of land-use developments was overlaid on the generated buffers, and the land-use developments within were extracted using ArcGIS Pro's "intersect" feature. The "intersected" data was imported in to Microsoft Excel, and the land-use area was summarized for each buffer ID corresponding to each bus stop using Excel's pivot table feature. Analysis was conducted for the physical land-use area and heated area.

Table 18. Land-use Development Categories

S. No.	Land-use categories
1	Agriculture
2	Airport
3	College
4	Government
5	Heavy commercial
6	Heavy industrial
7	Institutional
8	Light commercial
9	Light industrial
10	Medical
11	Multi-family residential
12	Office
13	Recreational
14	Resource
15	Retail
16	Single-family residential
17	Transportation
18	Unknown/vacant

6.3.1 Association Between Bus Transit Service Reliability and Land-use Area

Table 19 shows the Pearson correlation analysis results for the association between bus transit service reliability by day of the week, time of the day, and land-use characteristics within the bus stop vicinity. Bus transit service reliability has a statistically significant negative correlation with institutional and light commercial land-use categories within bus stop vicinity when analyzed at an aggregate level (all times of the day) on a weekday. This indicates that bus transit service reliability decreases as the institutional and light commercial areas by a bus stop increases. However, bus transit service reliability has a statistically significant positive correlation with light industrial, single-family residential, and total land-use areas when analyzed at an aggregate level (all times of the day) of a weekday. This indicates that bus transit service reliability increases as light industrial and single-family residential land-use areas within a bus stop vicinity increases.

For a weekday morning peak, bus transit service reliability has a statistically significant negative correlation with land-use categories like government, heavy commercial, institutional, light commercial, medical, and office areas within a bus stop's vicinity, indicating low bus transit service reliability at bus stops near high commercial/employment land uses. This may be attributed to trip attraction patterns at commercial/employment related land-use developments in the morning peak hour resulting in high travel time variations. However, there is a statistically significant positive correlation with light industrial, single-family residential and total land-use areas during weekday morning peak hours, indicating that bus transit service reliability increases as light industrial and single-family residential land-use areas within bus stop vicinity increases.

Table 19. Association between Bus Transit Service Reliability by Day of the Week, Time of the Day, and Land-use Development (Area)

Day of the week	Time of the day	Land-use category	0.25-mile buffer		0.50-mile buffer	
			BTR (-1 to 5 min.)	BTR (-1 to 3 min.)	BTR (-1 to 5 min.)	BTR (-1 to 3 min.)
Weekday	All	Institutional	-0.12		-0.1	-0.08
		Light commercial	-0.14	-0.1	-0.14	-0.1
		Light industrial	0.18	0.15	0.19	0.17
		Office				-0.12
		Single-family residential	0.14	0.13		
		Total	0.16	0.18	0.17	0.19
	Morning peak	Government	-0.11		-0.15	
		Heavy commercial			-0.1	-0.1
		Institutional	0.11	0.11	0.11	
		Light commercial	-0.12		-0.15	
		Light industrial	0.1		0.12	0.11
		Medical				-0.15
		Office	-0.16	-0.23	-0.17	-0.22
		Single-family residential	0.24	0.21	0.21	0.17
		Total	0.23	0.19	0.29	0.24
	Mid-day	Light commercial	-0.15	-0.09	-0.15	-0.1
		Office		-0.12		
		Single-family residential	0.18	0.14	0.11	0.08
		Total		0.15	0.11	0.17
	Evening peak	Agriculture	-0.12	-0.11	-0.08	-0.12
		Institutional	-0.16	-0.11	-0.19	-0.16
		Light commercial	-0.13	-0.14	-0.09	-0.1
		Light industrial	0.17	0.14	0.19	0.16
		Unknown/ vacant			0.16	0.16
	Night-time	Light commercial	-0.16			
		Recreational		0.13		
		Retail			-0.15	
		Single-family residential	0.11			
Weekend	All	Multi-family residential		0.13		
		Unknown/ vacant	-0.15		-0.16	-0.13
	Morning peak	Light industrial			-0.14	
		Multi-family residential		0.15		
		Unknown/ vacant	-0.15	-0.13	-0.14	
	Evening peak	Agriculture	0.14		0.13	
		Multi-family residential	0.18	0.18		
		Unknown/ vacant	-0.16	-0.12	-0.18	-0.14
	Night-time	Heavy commercial	-0.18	-0.1	-0.13	
		Retail	-0.14			
		Unknown/ vacant	-0.15		-0.14	

Note 1: BTR is bus transit service reliability.
Note 2: Correlation coefficients significant at a 95% confidence level are only summarized.

For weekday mid-day hours, bus transit service reliability has a statistically significant negative correlation with light commercial and office land-use developments within the bus stop vicinity. However, bus transit service reliability has a statistically significant positive correlation with single-family residential and total land-use area near bus stops on a weekday.

For weekday evening peak hours, bus transit service reliability has a statistically significant negative correlation with institutional and light commercial land-use developments. This indicates low bus transit service reliability at bus stops near commercial/employment land-use developments. However, bus transit service reliability has a statistically significant positive correlation with light industrial land-use developments.

For a weekday night-time hour, bus transit service reliability has a statistically significant negative correlation with institutional light commercial and retail land-use developments. This may be attributed to night-time shopping activities near the bus stop. However, there is a statistically significant positive correlation with single-family residential land-use development.

For a weekend, bus transit service reliability has a statistically significant positive correlation with multi-family residential land-use developments when analyzed at an aggregate level (all times of the day) as well as morning peak and evening peak hours. However, there is a statistically significant negative correlation with light industrial land-use developments for the morning peak hours. Likewise, bus transit service reliability has a statistically significant negative correlation with heavy commercial and retail land-use developments for the night-time hour, possibly due to shopping activities at night-time near the bus stop vicinity.

6.3.2 Association Between Bus Transit Service Reliability and Land-use Heated Area

A heated area is the living area of any land use. As stated previously, 0.25-mile and 0.5-mile radius buffers were generated around each bus stop, and land-use heated area was captured using ArcGIS Pro. Table 20 shows the Pearson correlation analysis results for the association between bus transit service reliability by day of the week, time of the day, and heated area of land-use developments within the bus stop vicinity.

Bus transit service reliability has a statistically significant negative correlation with institutional and multi-family residential land-use developments within the bus stop vicinity when analyzed at an aggregate level (all times of the day) on a weekday, indicating that bus transit service reliability decreases as the institutional and multi-family residential heated land-use areas within bus stop vicinity increases. However, bus transit service reliability has a statistically significant positive correlation with light industrial heated area when analyzed at an aggregate level (all times of the day) of a weekday, suggesting that bus transit service reliability also increases as light industrial land-use heated area increases.

Table 20. Association between Bus Transit Service Reliability by Day of the Week, Time of the Day, and Land-use Development (Heated Area)

Day of the week	Time of the day	Variable	0.25-mile buffer		0.50-mile buffer	
			BTR (-1 to 5 min.)	BTR (-1 to 3 min.)	BTR (-1 to 5 min.)	BTR (-1 to 3 min.)
Weekday	All	Institutional		-0.12		
		Light industrial	0.16	0.14	0.19	0.15
		Multi-family residential	-0.22	-0.19	-0.19	-0.21
	Morning peak	College			-0.11	-0.13
		Heavy commercial			-0.13	-0.12
		Institutional	-0.14	-0.19	-0.11	-0.15
		Light industrial			0.11	
		Multi-family residential	-0.22	-0.18	-0.23	-0.18
		Office	-0.12	-0.13	-0.11	-0.11
		Recreational			-0.11	-0.11
		Single-family residential	0.15			
		Total			-0.11	-0.11
	Mid-day	Airport		0.12		0.11
		Institutional	-0.13	-0.14		
		Light industrial		0.12	0.13	0.14
		Multi-family residential				-0.11
		Single-family residential	0.13			
	Evening peak	Light industrial	0.13	0.11	0.16	0.13
		Multi-family residential				-0.11
		Single-family residential			-0.12	
	Night-time	Retail			-0.13	
		Transportation		-0.12		
Weekend	All	Airport	-0.13		-0.14	
		Light industrial		0.14		
		Single-family residential	0.14		0.15	
	Morning peak	Airport	-0.15		-0.17	
		College	0.14		0.15	
		Single-family residential	0.18		0.18	
	Mid-day	Light industrial		0.17		0.13
	Evening peak	Retail		0.15		0.13

Note 1: BTR is bus transit service reliability.

Note 2: Correlation coefficients significant at a 95% confidence level are only summarized.

For a weekday's morning peak hours, bus transit service reliability has a statistically significant negative correlation with land-use categories such as government, heavy-commercial, institutional, multi-family residential, office, recreational, and total land-use heated areas near a bus stop. This indicates low bus transit service reliability at stops near commercial, residential, employment, and recreational land-use heated areas. However, there is a statistically significant positive correlation with light industrial and single-family residential land-use heated areas during weekday morning peak hours. This indicates that bus transit service reliability also increases as light industrial and single-family residential land-use heated areas within a bus stop vicinity increase.

For a weekday mid-day, bus transit service reliability has a statistically significant negative correlation with institutional and multi-family residential land-use heated areas within the vicinity of the bus stop. However, there is a statistically significant positive correlation with airport, light-industrial, and single-family residential land-use heated areas near bus stops on a weekday.

For a weekday's evening peak hours, bus transit service reliability has a statistically significant negative correlation with multi-family and single-family residential land-use heated areas within the bus stop's vicinity. This indicates low bus transit service reliability at bus stops near residential land-use developments. This may be attributed to trip end (destination) patterns in residential areas resulting in high variation in dwell time (boarding/alighting) and travel time (evening peak congestion). However, bus transit service reliability has a statistically significant positive correlation with light industrial land-use heated area. For a weekday's night-time hours, bus transit service reliability does not have a statistically significant correlation with land-use heated area.

For a weekend, bus transit service reliability has a statistically significant negative correlation with airport land-use heated area when analyzed at an aggregate level (all times of the day) and during morning peak hours near the bus stop. This may be attributed to high travel demand to airports on the weekends. However, bus transit service reliability has a statistically significant positive correlation with light-industrial and single-family residential land-use heated areas when analyzed at an aggregate level (all times of the day) within the bus stop vicinity. Likewise, there is a statistically significant positive correlation with college land-use heated area. For evening peak hours, bus transit service reliability has a statistically significant positive correlation with retail land-use heated area, indicating an increase in bus transit service reliability with retail land-use heated areas within the bus stop vicinity. For night-time hours, there is no statistically significant correlation with land-use heated area on a weekend, similar to a weekday.

7. Conclusions

Increasing travel demand and mobility challenges call for sustainable transportation approaches such as public transportation systems. Transportation planners and practitioners are interested in enhancing transit ridership and reliability to meet the increase in travel demand. However, recent statistics show a marginal decline in bus ridership. With an emphasis on multimodal and transit-oriented developments, there is a need to understand bus transit service reliability and its influence on ridership patterns.

The association between bus transit service reliability and ridership at a bus-stop level was examined using Pearson correlation analysis. Three hundred and ninety-four geospatially distributed bus stops in the city of Charlotte, North Carolina were considered. The research was conducted by categorizing the data using temporal factors (day of the week and time of the day), spatial indicators (direction of travel), and the type of bus stop. The OTP percentage is considered as an indicator of bus transit service reliability, and ridership is expressed as the average boarding of passengers (per bus) at a bus stop.

Two days of the week, four times of the day, two directions of travel, and five types of bus stops were considered for the Pearson correlation analysis in this study. The results show that ridership has a positive association with reliability for the selected days of the week and times of the day. Specifically, ridership during morning peak and night-time hours of a typical weekday are highly correlated with reliability, emphasizing concentrated work-trip patterns. In the case of the weekend, a moderate positive correlation between bus transit service reliability and ridership was observed for all times of the day.

The direction of travel was further used to examine the association between bus transit service reliability and ridership. A high positive correlation was observed for the inbound direction during morning peak hours on a typical weekday, potentially owing to work-trip patterns towards the city's central business district. Similarly, a positive correlation between bus transit service reliability and ridership for the outbound direction was observed during night-time hours, potentially due to work-to-home trips.

The presence of intermodal transit services in the city influences overall transit ridership and requires coordination for better reliability. The Pearson correlation analysis was conducted by classifying the data based on the type of bus stop to understand the influence of location parameters. The results indicate that transit centers and bus stops near LRT stations (typically categorized as high-activity bus stops) are positively correlated with ridership. A moderate positive correlation was observed at bus stops located away from LRT stations.

A spatial analysis was conducted to understand the effect of road, demographic, socioeconomic, and land-use characteristics on bus transit service reliability within the vicinity of a bus stop (0.25-mile and 0.5-mile radial buffers). The results show that the total number of signalized intersections are associated with bus transit service reliability within the vicinity of a bus stop. The negative correlation coefficient indicates low bus transit service reliability at bus stops that have a higher number of signalized intersections within their vicinity during weekday morning peak hours. Likewise, the total number of cul-de-sacs/dead ends near bus stops has a negative correlation with bus transit service reliability during weekday evening peak hours.

The results indicate that total road network length within the vicinity of a bus stop is negatively correlated with bus transit service reliability when analyzed at an aggregate level (all times of the day), during morning peak hours and mid-day of a weekday. This indicates that the bus transit service reliability decreases as the total network length within the bus stop vicinity increases (a denser network). However, for a weekend, bus transit service reliability is positively correlated with the total road network length in morning peak hours.

Population, the total number of household units, and the total number of employed persons near a bus stop have a negative correlation with bus transit service reliability during weekday morning peak hours. Also, total and median income levels within the vicinity of a bus stop have a negative correlation with bus transit service reliability during this same time frame, indicating low bus transit service reliability at stops in high-income areas.

Land-use areas with categories such as government, heavy-commercial, institutional, light-commercial, medical, and office areas have a negative correlation with bus transit service reliability during weekday morning peak hours, indicating low bus transit service reliability in high land-use development areas within the vicinity of a bus stop for the categories related to commercial/employment purposes. Light-industrial and single-family residential areas have a positive correlation with bus transit service reliability during weekday morning peak hours, which may be attributed to origin (residential area) and destination (commercial/employment area) trip patterns during morning peak hours.

Institutional and light-commercial land-use areas have a negative correlation with bus transit service reliability during weekday evening peak hours. However, single-family residential land-use areas have a positive correlation with bus service reliability during the same weekday time period.

Multi-family residential land-use areas have a positive correlation with bus transit service reliability during weekend morning and evening peak hours and all times of the day. However, heavy commercial and retail land-use areas have a negative correlation during weekend night-time hours.

Land-use heated areas were also used to understand the effect of land-use developments on bus transit service reliability. Institutional and multi-family residential land-use heated areas have a negative correlation with bus transit service reliability during weekday morning and evening peak hours and all times of the day. Further, for a weekday's morning peak hours, bus transit service reliability has a negative correlation with land-use heated area categories such as government, heavy commercial, institutional, multi-family residential, office, and recreational land-use heated areas within a bus stop's vicinity. However, light industrial and single-family residential areas have a positive correlation during this same time.

Multi-family and single-family land-use heated areas have a negative correlation with bus transit service reliability during weekday evening peak hours, possibly due to indicating end trip (destination) patterns in residential areas that result in high variations in dwell (boarding/alighting) and travel time (evening peak congestion).

Airport land-use heated areas have a negative correlation with bus transit service reliability during weekend evening and morning peak hours and all times of the day (aggregated). This may be attributed to high travel demand to airports on the weekends. However, for weekend evening peak hours, retail land-use heated areas had a positive correlation.

This research analysis examined the association between bus transit service reliability with ridership, road, demographic, socioeconomic, and land-use characteristics at a bus-stop level in Charlotte, North Carolina, but the methodological approach is transferable to other regions. It can be adopted to identify the significant characteristics of bus transit service reliability that influences ridership and can be used to understand any underlying external characteristics that may affect bus transit service reliability. The findings suggest that bus transit service reliability has a substantial impact on ridership and is influenced by all of the different analyzed characteristics within the bus stop's vicinity.

Transit agencies should continue to implement customer-oriented reliability and satisfaction measures. It is possible that the values placed on reliability and ridership may vary not only based on individual characteristics, but on regional characteristics as well.

7.1 Limitations and Scope for Future Research

Bus stops within a 0.25-mile radius of each LRT station were used here to analyze "bus stops related to LRT." However, bus stops located more than 0.25 miles away from an LRT station may also influence bus transit ridership, and these were not analyzed separately. The distance and location of all bus stops can influence the association between bus service reliability and ridership.

In this study, four selected hours of the day were used to examine the association between bus transit service reliability and ridership, but other times of the day (which would further increase the sample size) may be considered for better results.

The bus stops considered in this research are analyzed irrespective of their accessibility conditions (whether they are easily accessible or not) due to the data constraints. These conditions may be considered to better understand ridership and reliability patterns.

This paper analyzed the relationships between bus transit service reliability and the ridership data available per bus at a bus stop level. This research could be extended further by considering factors such as travel time, dwell time, and the bus’s capacity (number of passengers a bus can accommodate). These findings would be useful in bus transit service reliability model development considering road, demographic, socioeconomic, and land-use characteristics.

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