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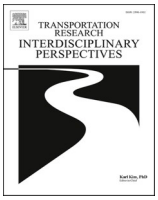

How do crime and neighborhood environment affect transit ridership? Evidence from five metropolitan cities in the Texas Triangle

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ABSTRACT

Transit ridership is an important factor in evaluating transit service performance and an essential source of revenue for transit authorities in the United States. Alongside internal service characteristics such as average headways and service frequency, the neighborhood environment context of transit-adjacent areas has been shown to affect ridership in many ways, with neighborhood crime being a major concern. Although literature recognizes the negative impact of crime on transit ridership, however, the roles of the neighborhood environment and the quality of transit service in affecting ridership have been less considered. Existing empirical evidence has been focused on a single geographical region. Using stop-level transit ridership and service characteristics data from transit agencies in five metropolitan areas in the Texas Triangle (Austin, Dallas, Fort Worth, Houston, and San Antonio) in 2018, we find that although the crime rate is negatively associated with ridership, better transit service characteristics such as higher service frequency and shorter average headway are associated with higher ridership, based on results of the negative binomial regression model. We also find that mixed-use development with greater population density, greater employment density, and employment entropy, as well as better walkability, are associated with higher transit ridership during workdays, holding all else constant. Our findings also show that block groups with challenging socioeconomic status (measured by households of lower income, households with public assistance, and unemployment status), are associated with higher transit ridership. Findings from this study contribute to strategies for sustainable fiscal health of transit agencies. Efforts to increase transit ridership should consider the built environment and social environment characteristics of the station-adjacent communities beyond service characteristics improvement.

Introduction

Public transit provides mobility options to essential destinations such as work, education, and medical care. For individuals and households with limited private mobility options, transit service provides essential accessibility (Bills & Walker, 2017; Karner, 2018; Karner et al., 2020). In addition to its importance for social equity and environmental justice (Karner et al., 2020; Litman, 2004), public transit use is also recognized for its benefits on more physical activity (Rissel et al., 2012), lower obesity rate (Brown et al., 2016; Brown et al., 2015), and environmental justice its association to less congestion and less air pollution) (Sallis et al., 2015). In addition to being an essential source of revenue, transit ridership is used for measuring the influence of transit system operational and infrastructure attributes (Chakour & Eluru, 2016). Understanding the factors that influence transit ridership could help planners and transit agencies improve transit operations and fair structures in building a transit-supportive environment.

Existing literature suggests that factors affecting transit ridership include both external and internal reasons (Taylor et al., 2009). External factors refer to factors that the transit operation system, or service management, cannot control, such as population density, land-use pattern, socioeconomic status, automobile ownership, highway system characteristics, etc. Internal factors refer to attributes that the transit system can adjust and control from its operation, such as the quality of service, fare policy, service coverage, operating hours, average headways, etc. Although there are debates about which factor is casting the leading influence (Dill et al., 2013; Taylor et al., 2009; Taylor & Fink, 2003), most agree that the environmental context in transit service is closely associated with ridership, which includes neighborhood crime.

Crime has long been identified as a main concern affecting people's attitudes toward using transit. Literature shows that among most transit-related surveys, people are more likely to feel "unsafe" on their way to

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take a bus or train rather than when they are riding the bus or the train (Cozens et al., 2003; Delbosc & Currie, 2012; Reed et al., 2000). Morse and Benjamin (1996) found that crime rates in the neighborhood census tract could significantly increase the feelings of insecurity about public transit based on their study in North Carolina (Morse & Benjamin, 1996). In addition to crime statistics, people's perception of crime and sense of safety could also be affected by neighborhood characteristics (including land use pattern, socioeconomic status, etc.) and lead to impacts on transit ridership. Notably, socially vulnerable populations, including Black, Indigenous, and People of Color (BIPOC), Hispanic or Latinx people, females, LGBTQIA + communities, recent immigrants, people with disability, and homeless populations, are more prone to be impacted by the fear of crime and hinder their use of transit service in daily life (Culbertson et al., 2001; Ding et al., 2022; Infante et al., 2012; Keane, 1998; Koskela & Pain, 2000; Loukaitou-Sideris, 2005; Loukaitou-Sideris & Fink, 2009; Lynch & Atkins, 1988; Núñez-González et al., 2020; Wilson-Genderson & Pruchno, 2013). During the aftermath of the COVID-19 global pandemic, the inequitable mobility challenge faced by historically disadvantaged populations has been exacerbated even more, as measured by recent mobility justice literature (Cochran, 2020; He et al., 2022; Palm et al., 2021; Ravensbergen & Newbold, 2020).

Although much of the literature has examined the relationship between crime and transit ridership, the internal service characteristics and external environmental factors have been less examined. Furthermore, there is little evidence across greater Metropolitan Statistical Areas (MSA) in the United States regarding the relationship between crime, land use, transit service characteristics, and ridership. This work improves the theoretical conceptualization of the relationship between crime and ridership, with transit ridership and service data from five metropolitan transit authorities in the Texas triangle (Dallas, Fort Worth, Austin, San Antonio, and Houston). Our sample size includes 23,823 transit stops across the five metropolitan areas. Crime incident data collected from local Police Departments were geocoded and aggregated into block group levels to represent the crime rates (including property crime and violent crime). We then quantify the density measurements, including residential density, population density, employment density, and road network density, to measure the land use characteristics in addition to the walkability index using the SmartLocation database developed by the U.S. Environmental Protection Agency. Findings of the negative binomial model show that although the crime rate could cast a negative impact on transit ridership, good transit service (lower service headway and greater number of trips per hour during the weekday), mixed-use development (greater population density, greater employment density, and employment entropy), and better walkability are associated with more ridership during the workday, holding all else constant. We also find that despite the impact of crime, neighborhoods block groups with challenging socioeconomic status (measured by households of lower income, households with public assistance, and unemployment status), are associated with higher transit ridership. This finding signals the need for transit service among essential transit users despite potential negative externalities such as crime risk.

We start with a literature review on transit ridership, its relationship with the built environment, social environment, and crime, followed by the theoretical positioning of this study. Then, we describe the data source, methodology, and modeling specification. After reporting the model output, we discuss the findings and conclude with implications for urban planning, transportation planning, and transit development.

Literature review

Existing literature examines the concept of transit ridership from two levels: macro-level and micro-level. The macro-level refers to factors affecting transit ridership from a regional or national scale, including multiple transit operation systems. The micro-level examines several metro or bus stations/lines within one particular study area, usually within one single transit authority. The majority of the literature is limited to system-specific studies. Although the findings from micro-level studies are important for understanding transit usage and ridership status, national-level studies could provide the overall knowledge of transit ridership and are important for transportation planning and policymaking. For example, Taylor et al. (2009) conducted a national survey in the United States, based on evidence collected from 264 urban regions. They found that factors such as regional geographical features, metropolitan-level economic status, population characteristics, as well as automobile/highway system characteristics are all associated with the transit ridership (Taylor et al., 2009). Alam et al. (2018) examined the determinants of travel demand by bus in 358 Metropolitan Statistical Areas (MSA) across the U.S. They found that transit operation factors (such as transit fare, transit supply, operation hours, headways, transit safety, and route coverage) significantly impact travel demand by bus (Alam et al., 2018). Meanwhile, more studies were conducted within the micro-level (Chan & Miranda-Moreno, 2013; Gutierrez, 2001; Lin & Shin, 2008; Ryan & Frank, 2009) using transit stop or line-level ridership data. Existing studies assess the influencing factors on transit ridership from a wide range, including the built environment, socioeconomic, transit system, and other factors (Alam et al., 2018). Among these factors, Taylor et al. (2009) classified them into Internal factors and external factors. We present the literature review tables for studies conducted on macro- and micro-level in the Supplementary Materials (see SM Table 2 and Table 3).

Internal factors affecting transit use

Studies argue for the internal determinant state that the improvement of service quality, system designs, fare system adjustment, and other operational efforts within the transit system can play an essential role in attracting transit ridership (Alam et al., 2018). Existing literature primarily measures the level of transit service from the supply perspective, mostly based on the measurement provided by transit authorities. For example, Cervero et al. (2010) used the number of daily metro rapid buses from both directions, the number of perpendicular daily feeder bus lines (both directions), and the number of perpendicular daily rail feeder trains to measure the level of service in Southern California (Cervero et al., 2010). Ryan and Frank used the number of bus routes serving a bus stop divided by the mean wait time of all routes serving the bus stop to examine the relationship between the pedestrian environment and ridership in the San Diego region, California (Ryan & Frank, 2009). Meanwhile, Chow et al. (2006) used the composite peak-hour headway, an average number of the bus serving each stop, the percentage of traffic analysis zone (TAZ) areas served by transit based on quarter-mile buffers around bus stops, bus route density (fee/per acre) in each TAZ, and the Number of Bus Routes in a TAZ (Chow et al., 2006). All of these factors appeared to have a significant and positive relationship with ridership measurement except for the composite peak-hour headway and the other TLOS stops in the catchment area. These studies are conducted on ridership data across multiple transit authorities, Metropolitan Statistical Areas (MSA), or across the nation (mostly in the United States). One of the most frequently used datasets is the National Transit Dataset (NTD), where aggregated ridership data could be obtained from 1991 to the current for each transit authority.

Results from macro-scaled studies find that internal factors associated with transit service could have significant impacts on ridership (Dill et al., 2013; Kain & Liu, 1999; Thompson & Matoff, 2003). Based on a stop-level case study from Portland, Eugene-Springfield, and Medford-Ashland area, Dill et al. (2013) found that the quality of transit service attributes (headways, hours of service, the transfer stops, etc.) have a greater impact on transit ridership when comparing with stop-level factors such as land-use characteristics (Dill et al., 2013). Kain and Liu (1999) conducted a study based on longitudinal data (1980 to 1990) in Houston, Texas, and San Diego, California, to examine the relationship between the fair policy and the change in transit ridership. They find

that service increases and fare reductions, as well as metropolitan employment and population growth, could cause large ridership increases in both study areas. In a national study of nine cities in the United States, Thompson and Matoff (2003) found that internal factors such as service coverage, service frequency, as well as multi-destination service orientations are some of the most powerful explanatory variables that are associated with the change in ridership.

Meanwhile, research evidence on the *micro-level* also supports the argument that internal transit factors play an important role in determining ridership. For example, using stop-level data from Montreal, Canada, Chakour and Eluru (2016) find that *transit headway* could affect ridership, while the *presence of other transit facilities* around the stop location could have a positive and significant effect on ridership. The findings from Chakour and Eluru (2016) are consistent with those from a macro scale, especially with Dill et al., 2013, arguing that internal transit service factors have greater impacts on transit ridership when compared with land use characteristics. Brown and Thompson (2008) use longitudinal data (1978–2003) from Atlanta, Georgia, to examine the impact of transit service and fare policies on transit ridership. The results show that *transit service and fare variables* have significant influences on transit ridership, and the elasticity is consistent with previous literature. Chan and Miranda-Moreno (2013) also found similar results in their longitudinal study in Quebec, Canada, that internal transit service factors (such as multi-modal connectivity, headways, etc.) have significant impacts on ridership from 1998 to 2003. Their finding shows that terminal stations and transfer stations are associated with a greater number of passengers alighting in a station during the morning peak hours (Chan & Miranda-Moreno, 2013).

Built environment and social environment

Beyond the internal factors reviewed above, Taylor et al. (2009) argue that external environmental factors have a greater impact on transit ridership. One of the most extensively examined external factors is *the neighborhood environmental characteristics*, especially the built environment. A rich body of literature has theorized and tested that built environmental factors play an important role in shaping peoples' travel behavior toward the public transit (Cervero, 2002; Ewing & Cervero, 2010; Handy et al., 2005; Krizek, 2003). Ewing and Cervero summarized that built environmental factors that affect transit use could be grouped into five categories ("5D"), including Density, Diversity, Design, Destination Accessibility, and Distance to the transit (Ewing & Cervero, 2010). Within the framework of "5D" variables, a vast amount of literature examined the impact of built environmental factors on transit ridership. Based on a case study in Twin Cities, Minnesota, Johnson (2003) found that vertical mixed-use development plays an important role in attracting ridership within a quarter-mile radius of transit service, indicating its similar importance as transit access and retail controlling for socioeconomic status and on-demand bus service. Lin and Shin (2008) found that commercial and retail land use, service areas, walkability around the transit stations, and the connectivity to transfer stations could attract transit ridership while controlling for other factors in Taipei, Taiwan (Lin & Shin, 2008). Ryan and Frank (2009) also find that walkability (measured by the mixed land use, density, and street pattern) around transit stations could help improve transit ridership based on the case study in San Diego, California (Ryan & Frank, 2009). In addition to the land use characteristics, street design pattern, and walkability, as well as the availability of parking spaces and bicycle standing areas also are shown to have a positive effect on the choice of the railway station (Debrezion et al., 2009).

Beyond neighborhood built environment, socioeconomic status around transit-adjacent neighborhoods is also shown to be associated with transit use and ridership. Taylor and Fink (2003) found that economic factors such as income level, employment status, and automobile ownership have a significant impact on transit modal shares and ridership. Debrezion et al. also noted that political support for the automobile industry and highway development on both federal and state levels can also affect transit use and ridership (Debrezion et al., 2009). Brown and Thompson (2008) observed that the rail ridership decline in Atlanta could be explained by the employment decentralization (Brown & Thompson, 2008). Similarly, Guerra and Cervero (2011) found that population and employment densities positively correlate with ridership after controlling for transit service attributes (Guerra & Cervero, 2011). Based on a case study in Los Angeles, California, Banerjee et al. (2001) found that bus ridership was positively associated with residential density, employment density, land use mix, and transit connectivity for two corridors in the Los Angeles area.

Crime as an element of urban Landscape

In the North American context, transit development has been traditionally characterized as a "crime attractor," "crime generator," and "fear generator" (Brantingham and Brantingham, 1991; Brantingham & Brantingham, 1995; Felson et al., 1996). However, the empirical evidence has been inconclusive in supporting the causal relationship between crime and transit facilities (He & Li, 2022; Loukaitou-Sideris et al., 2006; Plano, 1993; Poister, 1996; Ridgeway & Macdonald, 2017). Empirical studies examine the relationship between the sense of safety, or fear of crime, based on self-reported statements, for example, *"I might use public transport if I was happy about personal security"* (Crime Concern, 2004). Delbosc and Currie (2012) find that the sense of safety is positively related to how much people use public transit. On the other hand, studies find that the feeling of unsafety or fear of crime is associated with less transit use (Lynch and Atkins, 1988). However, there are also research findings show that the impact of crime and the fear of crime are relatively marginal when compared with the service characteristics such as the service frequency, reliability, and the cost of public transit, at least during the daytime (Mahmoud and Currie, 2010; Booz Allen Hamilton, 2007).

The impact of fear of crime affects people's travel behavior differently across different socio-demographic statuses, and this disparity functions particularly through the perception of safety towards transit use across different populations. For example, Delbosc and Currie (2012) find that the fear of unsafe when using public transit primarily stems from people's unsafe feelings about their living communities instead of about the station space or transit service area itself. More specifically, the feeling of insecurity or the fear of crime affects socially vulnerable populations disproportionately among women, older adults, recent immigrants, BIPOC, Hispanic/Latino community, as well as the LGBTQIA + population (Clarke & Lewis, 1982; Hanslmaier et al., 2018; He et al., 2022; Lynch & Atkins, 1988; Matherly and Mobley, 2011; Toseland, 1982). However, with the greater degrees of social and economic challenges, these groups of people are also more likely to have limited private mobility options and a greater tendency to rely on transit services. The dilemma between the need for transit service and the safety concern can bring additional burdens to the well-being of these historically marginalized populations.

Regarding the integrated impact of land use and crime, existing literature demonstrates conflicting outcomes. For example, Ferrell et al. (2008) studied the impacts of neighborhood crime on the non-auto mode of travel choice after controlling for land use variables in seven cities in the San Francisco Bay Area, California. They find a negative association between transit use in suburban cities for both commuter and non-work with both the vice and vagrancy crime rates. However, Ferrell and Mathur (2012) found in a later study that this relationship can be reversed.

Data and methodology

The outcome variable of this study is the stop-level ridership (2018) of transit authorities from Dallas, Fort Worth, Austin, San Antonio, and Houston (n = 23,823), the five largest Metropolitan cities in the Texas

Triangle. Geographically, the Texas Triangle is a region that contains the state's five largest cities and the home to the majority of the population in Texas (see Fig. 1). Considering its economic and sociodemographic significance, researchers identify Texas Triangle as one of the eleven megaregions in the United States according to the book "Megaregions and America's Future" by Yaro et al. (2022), with the cluster of urban regions sharing economic and cultural ties. In 2010, the population of the Texas Triangle was 19.7 million, accounting for 6 % of the U.S. total population. The research evidence from this research area can provide similar implications for other metropolitan, or megaregions in the U.S. regarding transportation planning and transit development.

We selected our study area based on its potential to provide insights into transit ridership patterns and the impacts of various factors such as crime rates, neighborhood built environment, and socioeconomic status across diverse urban forms. The five cities in the Texas triangle can be representative of many metropolitan areas in the U.S., given their diverse urban forms and rapidly growing population trends. To our knowledge, there has been no study analyzing the relationship between transit ridership and crime in this area, despite several case studies on the individual cities. Zhang, (2016) used a path analysis model to examine the relationship between land use, crime, and bus ridership in Austin, TX. They found that population density and mixed-use development were positively related to crime rates and had a non-linear effect on ridership. Specifically, crime rates started to negatively affect bus ridership once they exceeded a certain threshold. Similarly, Li et al. (2019) used a Random Forest Ensemble Algorithm to examine the criminal factors affecting bus ridership in Houston, TX, another metropolis in the Texas Triangle. Based on data from 2015, their findings indicated that medium and lower ridership levels were positively correlated with crime rates. This suggests that reducing crime per capita can help promote bus ridership. With a significantly larger sample size focusing on the fast-growing Texas Triangle region, we aim to provide greater insight into understanding how neighborhood environment and service characteristics can condition crime's effect on transit ridership.

The ridership dataset was collected from five transit agencies: Dallas Area Rapid Transportation (DART), Trinity Metro, Capital, Via, and Metro for the target research period (August 2018). To measure the service characteristics of each transit station within the examined transit agency, we obtain the transit General Transit Feed Specification (GTFS) data from transit authorities as well as the Open mobility data portal. We then use the *BetterBusBuffers* toolbox developed by Esri to process and analyze the GTFS data. More specifically, we use the "The Count Trips at Stops tool" to calculate the Number of Trips per Day and the Number of Trips per Hour. This tool counts the number of transit trips that visit the stops in the network during a time window (24 h on a workday).

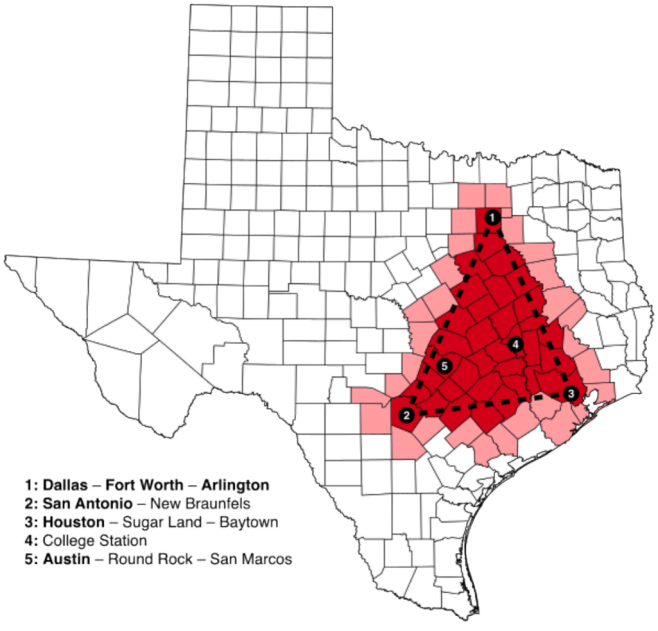

Fig. 1. Illustration of the research area and the Texas Triangle ().
Source: Wikipedia

Crime incident reports were collected from the public data portal or Public Record Requests through each city and police department for the year 2018. These crime data are then geocoded and aggregated into block group levels, including both property crime and violent crime. We use the urban density measurements retrieved from the SmartLocation Database developed by the Environmental Protection Agency. Based on the literature review, we retrieve measurements including *residential density, population density, employment density,* and *road network density*, to measure the land use characteristics in addition to the *walkability index*.

Demographic and socioeconomic measurements were obtained and processed from the U.S. Census American Community Survey (2018, 5-Year Estimates) for each block group. We use the spatial location identify tool in Esri ArcMap 10.7 to select the block group that transit station is located upon. The built environmental and social environmental variables, as well as the crime statistics of each block group, were then joined by the transit station level, using spatial location references. Fig. 2 demonstrates the research conceptualization and the measurements applied in this study.

Given that the dependent variable is a count variable with non-negative integer values, General Linear Regression models (GLM) stand out as an ideal option for the regression analysis (Cameron & Trivedi, 1990; Wooldridge, 2012; Zhang et al., 2018) without having to meet the distribution assumptions for Ordinary Least Square model. Within the two types of GLM, the assumptions for Poisson regression would require that the mean value (μ) should equal the standard deviation (σ) in the dependent variable (Cameron & Trivedi, 1990; Wooldridge, 2012), which does not apply in our dataset. Hence, the Negative Binomial is the better fit based on the data condition and analytical purpose of this study. After using Pearson correlation tests to test for collinearity, we conduct the Negative Binomial Regression analysis and present the results below.

Findings and Discussion

We present the Negative Regression Model output in Table 1, with green highlight marking coefficients showing significantly positive relationships with ridership and yellow highlight marking coefficients showing significantly negative relationships with ridership. We find that the stop-level ridership is significantly affected by transit service characteristics. Specifically, the results show that transit trips per hour are positively related to the ridership, and the average headway is negatively related to the transit ridership, holding all else constant. This is consistent with our hypothesis that the convenience of using transit with higher frequency and less waiting time would encourage transit use. The number of crimes within the block group shows a negative association with the ridership. This suggests that in neighborhoods where are higher crime rates, the transit stop tends to have lower ridership. This finding is consistent with the literature in terms of crime's impact on transit use. Intuitively, higher crime rates may increase the perception of unsafety, and discourage people from using transit services in the associated areas. Another potential indication is that areas with higher crime rates might also have environmental characters, such as physical signs of deterioration, which might not be captured from the land use perspective in this study.

Regarding the impact of the neighborhood built environment on transit ridership, we find that block groups with higher population density, higher employment density, and higher employment entropy, tend to have better ridership outcomes. Block groups with higher residential density (household units per acre) are associated with less transit

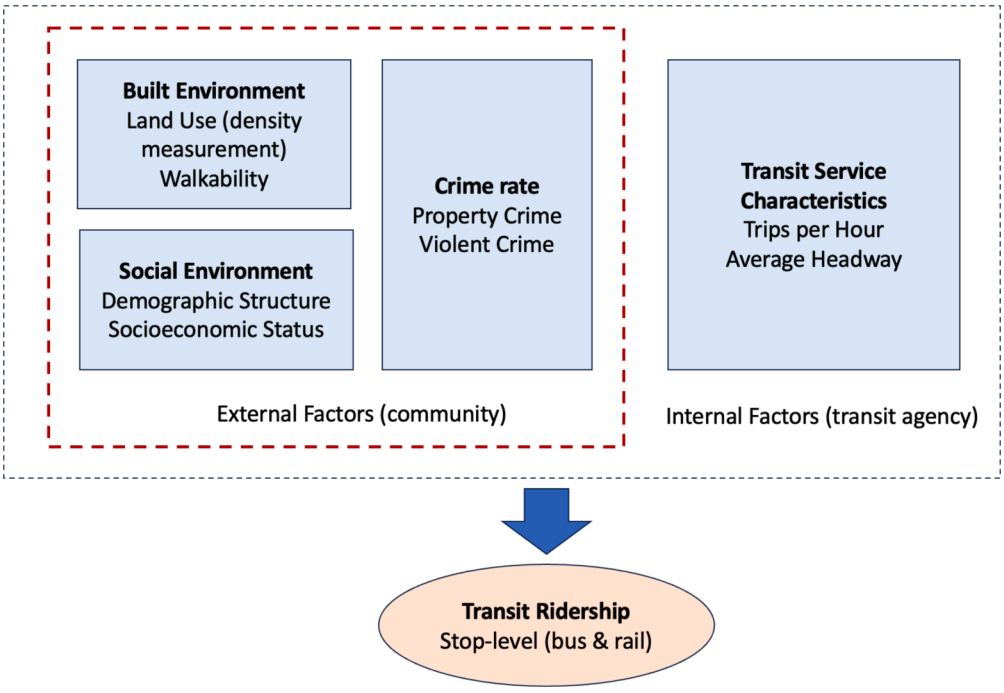

Fig. 2. Theoretical diagram of research design.

Table 1
Regression output from the negative binomial model.

Log (Ridership)	Coef.	Robust Std. Err.	P > Z
#Transit Trips per Hour	0.0335	0.0046	**<0.01** ***
Average Headway	−0.0004	0.0001	**<0.01** ***
Log Crime	−0.0413	0.0119	**<0.01** ***
Log Crime square	0.0005	0.0014	0.7300
Residential density	−0.0095	0.0026	**<0.01** ***
Population density	0.0028	0.0011	**0.0130****
Employment density	0.0009	0.0002	**<0.01** ***
Employment entropy	0.1056	0.0158	**<0.01** ***
Road network density	0.0012	0.0006	0.0630
Walkability Index	0.0158	0.0018	**<0.01** ***
Median income	−8.44E-07	1.62E-07	**<0.01** ***
Unemployment population	0.0004	0.00007	**<0.01** ***
Household with Public Assistance	0.0006	0.0001	**<0.01** ***
Renter Household	−0.00004	0.00002	0.0680
Household without a Vehicle	−6.84E-06	0.0001	0.9160
African American and Black population	−0.0002	0.00001	**<0.01** ***
Asian population	0.0002	0.00002	**<0.01** ***
Hispanic or Latinx	−7.77E-06	9.38E-06	0.4080
Non-Hispanic White alone population	−0.0001	0.00001	**<0.01** ***
# Jobs in Labor industry	−0.0001	0.00003	**0.0280****
# Jobs in Retail industry	−0.0003	0.00004	**<0.01** ***
# Jobs in Professional industry	0.0001	0.00003	**<0.01** ***
# Jobs in Service industry	0.0005	0.00002	**<0.01** ***
_cons	1.2588	0.0368	<0.01 ***
Model Summary Statistics /lnalpha	−5.1365	0.544441	
alpha	0.0059	0.0032004	

Log pseudolikelihood = −45509.74; Wald chi2(24) = 2708.24; Prob > Chi2 = 0.000; Pseudo R2 = 0.0435.

ridership. This may be due to that areas with more housing units are not necessarily the major origin or destination for transit trips. Another potential reason might be the availability of alternative mobility options in areas with higher residential density, such as walking or biking (Mattson, 2020).

From the socioeconomic perspective, model finding shows that transit stops within neighborhoods with a higher unemployment population, more households with public assistance, and less median household income demonstrate higher ridership in the adjacent transit stops, holding all else constant. This result echoes the argument that socially challenged populations tend to have greater needs for public transit service, due to constraints in private mobility options (He et al., 2022; Karner et al., 2020; Taylor & Morris, 2015).

Our finding demonstrates a mixed picture of the relationship between the neighborhood racial profile and the transit ridership. We find that block groups with a higher African American and Black population are demonstrating lower ridership, and that block groups with non-Hispanic White alone are also negatively associated with ridership. Meanwhile, we find that block groups with higher Asian American populations are associated with higher ridership, holding all else constant.

Previous literature shows that neighborhoods with concentrated disadvantage tend to have relatively weaker collective efficacy; hence are more likely to feel a sense of insecurity within neighborhood surrounding areas (Sampson et al., 1997; Sampson and Groves, 1989). The growing body of literature on transportation justice is revealing how transportation inequity is an outcome of historical and contemporary racism in urban planning, public policy, development projects, and the decision-making process (Barajas, 2021; Karner et al., 2020). Historic racist practices in public policy and urban planning decisions, such as redlining, have created concentrated disadvantage and disinvestment among people of color communities, especially Black communities in the U.S. The outcome of spatial segregation and opportunity exclusion have hence led to a higher rate of physical disorders and community security (Sampson and Groves, 1989; Sampson et al., 1997), which can further hinder the ridership of public transit.

Our finding on the positive relationship between the Asian American population and transit ridership provides new evidence to the growing field of travel behavior among different Asian American population groups. The literature on the travel behavior among Asian Americans, considering various immigration statuses, is relatively scarce. Existing study identifies that the travel preferences among Asian Americans, especially Asian immigrants, differ from other racial and ethnic groups (Hu, 2017). White established Asian immigrants (who have lived in the

U.S. for more than four years) are prone to adjust to the car-dependent lifestyle (Blumenberg & Shiki, 2007; Hu, 2017), while recent immigrants tend to use public transit use more often. This could either be due to a greater likelihood of experiencing constraints in personal mobility choices when people just moved to the U.S. or due to a cultural preference coming from more transit-friendly environments in Asian countries.

Results on the employment occupation indicate that stations in block groups with more jobs in labor and retail industries are associated with less ridership, while more jobs in professional and service industries are associated with higher ridership, holding other factors constant. Due to data limitations, we are not able to test for the difference in relationships between rail service and bus service. However, our findings are consistent with the previous literature in signalizing the difference of transit service coverage between different job sectors (Brown et al., 2014; Taylor & Morris, 2015), especially the disparity between white-collar workers and the lower-compensation jobs such as in labor or retail industry. This relationship can be examined from two perspectives. From the built environment perspective, employees from the high-paying sectors (such as professional services, finance, and IT industries, etc.) are more likely to cluster around the Central Business District (CBD) and other areas with better transit amenities. From the service provider perspective, the transit service coverage tends to develop greater coverage for white-collar workers, with an emphasis on commuter ridership, which can leave gaps for lower-paying jobs and people with blue-collar industries. Future studies should investigate this area, especially to consider the needs of "essential transit riders", namely those who rely on transit service the most.

These coefficients demonstrate statistically significant relationships between the independent variables and ridership, indicating that variations in these variables are reliably associated with variations in ridership levels. However, it is important to note that the magnitudes of these coefficients are relatively modest, suggesting that while the relationships are meaningful, their practical impact on ridership may be limited. This highlights the need for a nuanced interpretation of the results, considering both statistical significance and effect magnitude.

To account for potential variations in crime rates, ridership, and other geographical characteristics across cities, we constructed five Negative Binomial Regression models, one for each city in our study area. The results of these models are presented in Supplementary Material Tables 6 to 10. One key insight from the city-level regression outputs is the significant variability in the significance and signs of coefficients when analyzing each city individually. Findings from the aggregated NBR model may differ when considering individual cities. For instance, the relationship between crime and ridership exhibits diverse patterns across locations. While the aggregated model suggests a linear negative relationship between crime rate and ridership, the models for Dallas, San Antonio, and Houston reveal non-linear and sometimes reversed relationships. Specifically, in Dallas and San Antonio, transit ridership is positively correlated with crime—where higher crime aligns with higher ridership—until a certain crime threshold is reached, after which ridership declines with increasing crime rates. In contrast, Houston demonstrates a consistently negative relationship, where higher crime corresponds with lower ridership, until a specific crime threshold is surpassed.

These discrepancies may be attributed to the distinct crime patterns observed across the cities, as illustrated in Supplementary Material Fig. 1. It is essential to acknowledge that variations in crime reporting systems across cities, influenced by geopolitical contexts and local administrative cultures, can affect the collection, reporting, and documentation of crime data, and potentially lead to the differences observed in our models. Additionally, underlying factors such as public perceptions and norms regarding crime and safety in transit environments may vary significantly across the geopolitical contexts of these five cities. Further research utilizing longitudinal data is needed to explore potential causal relationships and to enhance our understanding of the common themes and differing patterns across these urban areas.

Conclusion and implications

Public transit connects people to well-being by determining destinations such as work, school, grocery, and healthcare. Beyond the functionality benefits, public transit also helps mitigate the climate crisis by lowering the carbon emissions of private vehicles. Additionally, public transit use has been found to promote active and healthy lifestyles among urban communities. Furthermore, transit service is essential to social justice by providing mobility options for those with limited mobility options due to socioeconomic status, physical or mental disability, or immigration status.

As an element of urban-scape, crime affects people's travel behavior directly and indirectly. Although long been examined as an external factor for travel behavior, less is known regarding the joint effect of crime and transit service characteristics after controlling the built environment and social environment. Understanding the role of crime within the context of transit service and the neighborhood environment is crucial to ensure transit service achieves an ideal ridership outcome.

In this study, we use stop-level transit ridership and service characteristic data from transit authorities within five metropolitan cities in Texas: Dallas, Fort Worth, Austin, San Antonio, and Houston, with a dataset consisting of 23,823 transit stops. The negative binomial regression model results show that the crime rate is negatively associated with ridership after controlling for all other factors. As the literature states, crime could affect ridership by triggering a greater sense of insecurity toward public space and public transit. Our finding indicates that investing in a safe and secure transit environment can play of critical role in promoting more transit use and improving trip satisfaction among transit users.

We also find that good transit service characteristics and vibrant urban built environmental factors could help mitigate the negative effect that crime rates can have on transit ridership. Greater quality of transit service, with more trips per hour during the weekday and shorter average headway, is shown to have a positive association with ridership during the workday, holding all else constant. In addition to the consistency in the findings with existing literature regarding "better service attracts more ridership", our finding generates new evidence to support the argument that areas with greater urban density (population density and employment density), mixed-use development (employment entropy), and better walkability could help facilitate more transit use after controlling for the impact of crimes. Our results suggest mixed relationships between transit ridership and different types of job occupations, with higher-paying employment sections, such as professional and service employment, associated with higher ridership, versus employment in labor and retail, showing negative associations. This finding can potentially point to the equity concern regarding job accessibility among lower-paying employment opportunities, such as in the labor and retail industry, as Taylor and Morris argued (Taylor & Morris, 2015).

We also find that block groups with households of lower income or with public assistance, as well as unemployed people, are associated with higher transit ridership. This result corresponds to the equity concern regarding racial equity (Barajas, 2021), where the racially disadvantaged population, such as the Black community, might experience greater barriers to transit use.

Finally, findings on the impact of crime on transit ridership remind us consideration about the potential outcome of policing efforts and Crime Prevention Through Environmental Design (CPTED) practice upon the sense of space, as well as the perception of (un)safety, especially among transit riders. The direct impact of crime is primarily generated through victimization and witnessing victimization, which account for a statistically smaller portion of the population. However, to the vast majority of transit riders, crime affects our sense of insecurity through "perceptions" in daily life. How people feel about the space that they're in is largely conditioned by the urban built environment (such as

land use, design, physical order, etc.) and social environment (such as social cohesion, sense of economic deprivation, etc.). Some commonly suggested crime-preventing practices in the literature, such as strengthening patrolling and law enforcement by expanding the funding budget for the police department, may fall short in considering the impact on people's perception of public space. These surveillance practices could lead to unintentional consequences by triggering a greater "fear of crime" and "sense of insecurity" despite the crime statistics. Future research should explore the potential impact of law enforcement on people's perception of safety among transit services and station areas and the ultimate effect on transit use across different rider populations.

While our analysis provides valuable insights into the trends within the available timeframe, it is important to acknowledge the data limitation that potentially constrains the timeliness of the findings. Analyzing crime types by separating property and violent crime can provide more nuanced insights. While this work focuses on the general crime pattern, we suggest that future research explore the differentiated impacts of violent and property crime on transit ridership to better understand their separate influences. Given our dataset's extensive sample size and broad geographic coverage, including crime and transit data across five metropolitan areas, we could not retrieve complete data points across our study area beyond the study time of 2018. We note this limitation and believe it is important for further research with the more recent dataset to test the empirical findings from this work. Notably, the pandemic has had profound effects on transit systems worldwide. Budget deficits and service cuts resulting from reduced ridership and increased health and safety concerns might have affected the availability and reliability of transit services (Karner et al., 2023). These changes could have led to shifts in transit ridership patterns, as reduced service frequency and coverage deter use or shift riders to other modes of transportation (He et al., 2022; Palm et al., 2021). Additionally, the post-pandemic rise in remote work has altered traditional commuting patterns. Many individuals who had previously relied on or preferred using public transit for daily commutes may now work from home, leading to a decrease in overall ridership. This shift could be a significant factor in understanding current transit use trends and planning future services.

Findings from this study contribute to strategies for sustainable fiscal health of transit agencies, given that transit ridership is a crucial revenue source of local transit operations. Transit service and its catchment area cannot exist in a vacuum environment. Efforts to improve transit ridership should also consider the built environment and social environment characteristics of the station-adjacent communities. Improving transit service characteristics such as frequency and headways, as well as creating a safe, vibrant, and walkable community environment through urban planning and community development efforts, can have significant outcomes in increasing transit ridership performance.

Data sharing Plan

Data will be made available on request.

CRediT authorship contribution statement

Qian He: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation. **Jianling Li:** Writing – review & editing, Validation, Methodology, Investigation, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trip.2024.101311.

Data availability

Data will be made available on request.

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