Evaluating Transit Accessibility to Food, Education, Recreation, and Other Essential Services in Tennessee

RES 2023-09

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Numerous prior studies have evaluated transit accessibility to job opportunities. Although providing access to jobs is an important function of public transit, other travelers use transit to get to grocery stores, healthcare facilities, schools, childcare, or outdoor recreational areas, which are not typically considered in transit accessibility analyses. These destinations are essential for independence, health, and quality of life. Therefore, this research aims to analyze transit accessibility and transit equity to access essential services or essential destinations and identify areas of concerns with limited transit accessibility and high potential transit demand. This research includes fixed-route transit (FRT) accessibility analyses in four large urban cities in Tennessee (Nashville, Memphis, Chattanooga, and Knoxville) and a demand response transit (DRT) accessibility analysis in one small urban area in Tennessee (Morristown). The results reveal specific areas of concern with limited transit accessibility and/or access to essential services/destinations.</td></tr>
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An important part of research is dissemination of the methods and results to other researchers and practitioners. The following is a list of research products that are associated with this project. Additional venues for dissemination of the research findings will be added in the future as appropriate.

Papers:

1. Guo and Brakewood (2023). “Analysis of spatiotemporal transit accessibility and transit inequity of essential services in low-density cities, a case study of Nashville, TN,” *Transportation Research Part A: Policy and Practice*. Volume 179. Open access article available here: https://doi.org/10.1016/j.tra.2023.103931

2. Guo, Mishra, Brakewood (2024). “Analyzing gender and age differences in travel patterns and accessibility for demand response transit in small urban areas: A case study of Tennessee.” *The Journal of Transport and Land Use*. Volume 17, No. 1, pp. 1-21. Open access article available here: https://doi.org/10.5198/jtlu.2024.2454

Presentations:

1. Guo and Brakewood (2024). “Analysis of spatiotemporal transit accessibility and transit inequity of essential services in low-density cities: A case study of Nashville, TN,” Lectern presentation at Transit Data 2024, London, England.

Executive Summary

Disadvantaged populations often rely on public transit for their transportation needs. Numerous prior studies, including TDOT project RES2021-08, have evaluated transit accessibility to job opportunities. Although providing access to jobs is an important function of public transit, many travelers use transit to get to grocery stores, healthcare facilities, childcare, schools, or outdoor recreational areas, which are not typically considered in transit accessibility analyses. These destinations are essential for independence, health, and quality of life. Research is needed to evaluate the transit accessibility to food, healthcare, childcare, education, and other essential services in Tennessee to help better understand the value of transit for riders. Therefore, this research aims to analyze transit accessibility and transit equity to access essential services or essential destinations and identify areas of concerns with limited transit accessibility and high potential transit demand. This research includes fixed-route transit (FRT) accessibility analyses in four large urban cities in Tennessee (including Nashville, Memphis, Chattanooga, and Knoxville) and a demand response transit (DRT) accessibility analysis in one small urban area in Tennessee (Morristown).

This project had the following research objectives:

- **<u>Objective 1:</u>** Review new literature on transit accessibility with a focus on access to essential services, demand response transit accessibility, and transit equity;
- **<u>Objective 2:</u>** Compile data from various sources, such as transit service data (both FRT and DRT); demographics, and the locations of food stores, healthcare facilities, schools, parks, and/or other essential services in Tennessee;
- **<u>Objective 3:</u>** Analyze spatial and temporal access using fixed route transit (FRT) services to the locations of food stores, healthcare facilities, schools, parks, childcare, and/or other essential services in areas with high potential transit demand (e.g., larger low-income populations) in the four major urban areas of Tennessee;
- **<u>Objective 4:</u>** Analyze accessibility of demand-response transit (DRT) services in a small urban area of Tennessee;
- **<u>Objective 5:</u>** Identify areas of concerns that have inequitable transit access to essential services and evaluate improvements to transit service that could increase access.

Key Findings

The key findings are briefly described in the following paragraphs.

1. <u>Results of the literature review</u>

The literature review on fixed route *transit accessibility to essential services* revealed the critical role of accessibility to essential services to improve the quality of life of individuals, which can be measured using different approaches. Prior research commonly employed a time-based approach to measure transit access to essential services, as it mirrors the actual travel behaviors of accessing essential services (people might care more about the travel time to access the nearest service facility instead of the number of services facilities accessible within a given time threshold). Therefore, in this study, a time-based approach is applied in the transit accessibility calculations. The literature review on *transit accessibility to essential services* also revealed that ignoring temporal variations in evaluating transit access to essential services may lead to inaccurate results, potentially resulting in incomplete and inadequate planning for future transit system changes. Therefore, building on prior research, this study proposes a comprehensive spatiotemporal transit supply index that weights transit accessibility by the effects of temporal variations on transit accessibility observed within the study areas.

Second, the literature on fixed route *transit equity* revealed that previous studies examining transit equity to essential services have yielded varied findings, and most prior studies focused on dense cities with well-established transit networks, particularly heavy or light rail systems. Therefore, the analysis conducted in this project provides a valuable addition to the existing literature by examining the transit equity to essential services in lower-density urban areas with primarily bus-based transit systems in Nashville, Memphis, Chattanooga, and Knoxville. Additionally, the term "transit desert" has been extensively discussed in prior literature and is generally defined as geographic areas or locations that have limited transit accessibility to a specific type of service, such as "food deserts". However, few prior studies have quantified transit equity to access multiple essential services; therefore, the concept of "essential service deserts" is proposed in this paper to identify areas with limited access to numerous essential services.

Last, the literature review also included transit accessibility measures and transit desert identification for demand response transit (DRT), which is typical in less populated areas. There is a noticeable gap in the prior research on accessibility analyses for DRT. In this report, DRT accessibility is quantified as the travel distance that was recorded in real-world DRT trip data. The use of actual travel distance from DRT trip data ensures the repeatability of the methodology across DRT systems in other areas. Based on the prior literature of transit deserts, there are different methods to understand the relationship between transit demand and transit accessibility to identify areas of concern. One prior study evaluated areas with high public transit demand but limited public transit accessibility using a quadrant classification method, which categorized regions into four classes based on their levels of transit demand and accessibility. This classification method proved to be relatively simple to construct yet highly effective in producing meaningful outcomes. Therefore, the proposed "essential destination" deserts analysis used in this study employs a quadrant classification to spatially identify potential areas of concern with high DRT demand and limited DRT accessibility.

2. Results of the spatiotemporal transit accessibility of FRT to essential services

This research analyzed the spatiotemporal FRT accessibility to the locations of food stores, healthcare facilities, childcare facilities, schools, and parks in areas with higher potential transit demand (i.e., larger populations with limited personal vehicles, those living in poverty and minority populations) in the four major urban cities in Tennessee (including Nashville, Memphis, Chattanooga, and Knoxville). The spatiotemporal transit supply index was proposed based on the spatial transit accessibility (measured by travel time) and the temporal variation of transit accessibility. The maps of spatiotemporal transit supply levels revealed several noteworthy spatial patterns. First, the downtown area always had the highest transit supply levels regardless of the essential service category. Second, areas with denser transit stops and more essential service facility locations generally corresponded to higher transit supply levels (as would be expected). Third, there was a consistent trend of decreasing transit access to food, healthcare, school, and childcare as one moves away from the city center and towards the outskirts of the city, particularly in Nashville. Also, the distribution of transit supply to access parks was somewhat different from other essentials services in Nashville; this is likely because recreational amenities and green spaces, particularly larger parks, are often located in suburban areas of Nashville. In the other cities, transit supply for accessing healthcare stood out as being distributed differently from the transit supply for accessing the other four essential services in Memphis, Chattanooga and Knoxville. Based on these findings, it can be concluded that certain areas in each of the four cities had limited access to one or several types of essential services via transit.

3. <u>Results of the transit accessibility of DRT</u>

In Morristown, the spatial distribution of DRT accessibility, as indicated by DRT trip distances, showed a scattered distribution, unlike fixed-route transit, which typically exhibited a gradual decrease in accessibility from the urban center or bus stops towards the city outskirts. However, DRT accessibility to essential destinations was typically spatially related to the location of facilities. Specifically, DRT trips to essential destinations typically displayed shorter trip distances in residential areas closer to destination facilities.

4. <u>Results of the identification of essential service deserts with limited FRT accessibility</u>

To identify essential service deserts characterized by low FRT supply and higher potential transit demand, the bivariate local indicator of spatial association (bi-LISA) was utilized to evaluate the spatial disparity of the relationship between transit supply to access essential services and potential transit demand across Census block groups and to identify spatial clustering of transit inequity. The bi-LISA spatial clustering further identified essential service deserts and indicated that different spatial distributions of essential service deserts were observed across cities. In Nashville, areas with higher potential transit demand were more likely to have limited transit access to food stores, healthcare, school, and childcare categories than to have limited transit access to parks. Most essential service deserts were notably concentrated in the north edge of Chattanooga. However, Knoxville had some essential service deserts positioned closer to the city center. When conducting a cross-sectional comparison in Memphis, there was only a slight difference in transit supply to access specific essential services for different demand groups. This might result from the fact that transit demand in the three population groups exhibited a relatively similar spatial distribution in Memphis.

5. <u>Results of the identification of potential areas of concerns with limited DRT accessibility</u>

A quadrant classification was used to identify potential areas of concern with limited DRT accessibility and high DRT trip demand in Morristown. The results identified "essential destination deserts" and revealed distinct spatial variations between some demographic groups (specifically, the elderly and females). The classification results also illustrated certain areas displaying varying spatial relationships between DRT demand and DRT accessibility when accessing different essential destinations (i.e., healthcare, leisure, and service destinations). The identification of these potential areas of concern is important to ensure equitable accessibility to DRT services in future transportation planning and the development of service facilities.

Key Recommendations

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Glossary of Key Terms and Acronyms

- FRT: Fixed Route Transit
- DRT: Demand Response Transit
- Bi-LISA: Bivariate Local Indicator of Spatial Association
- GIS: Geographic Information System
- GTFS: General Transportation Feed Specification
- WeGo: WeGo Public Transit (Nashville)
- MATA: Memphis Area Transit Authority
- KAT: Knoxville Area Transit
- CARTA: Chattanooga Area Regional Transportation Authority

Chapter 1 Introduction

1.1 Background

Disadvantaged populations often rely on public transit for their transportation needs. Numerous prior studies, including the TDOT project numbered RES2021-08, have evaluated transit accessibility to job opportunities. Although providing access to jobs is an important function of public transit, many travelers use transit to get to food stores, healthcare facilities, childcare facilities, schools, or outdoor recreational areas, which are not typically considered in transit accessibility analyses. These destinations are essential for independence, health, and quality of life. Research is needed to evaluate transit accessibility to food, healthcare, childcare, education, recreation, and other essential services in Tennessee. To better understand how current transit services meet the needs of disadvantaged groups across the state, it is necessary to analyze spatiotemporal transit accessibility to different essential services like food stores, health services, schools, childcare and parks. In addition, Demand Response Transit (DRT) services play a crucial part in transportation systems in less populated regions; however, there is a noticeable research gap in accessibility analyses for DRT and limited existing methods to evaluate DRT accessibility to essential destinations.

1.2 Objectives

The overarching objective of this research project is to critically evaluate fixed route transit (FRT) accessibility in the four major cities of Tennessee and assess demand response transit (DRT) accessibility in one less populated area in Tennessee. The specific objectives are as follows:

- **Objective 1:** Review new literature on transit accessibility with a focus on access to essential services, demand response transit accessibility, and transit equity;
- **Objective 2:** Compile data from various sources, such as transit service data (both FRT and DRT); demographics, and the locations of food stores, healthcare facilities, schools, parks, and/or other essential services in Tennessee;
- **Objective 3:** Analyze spatial and temporal access using fixed route transit (FRT) services to the locations of food stores, healthcare facilities, schools, parks, childcare, and/or other essential services in areas with high potential transit demand (e.g., larger low-income populations) in the four major urban areas of Tennessee;
- **Objective 4:** Analyze accessibility of demand-response transit (DRT) services in a small urban area of Tennessee;

  Objective 5: Identify areas of concerns that have inequitable transit access to essential services and evaluate improvements to transit service that could increase access.

1.3 Scope of Work

The scope of work was divided into seven primary tasks, which are briefly described below.

- **Task 1: Review new literature**

  The first task included a detailed review focusing on the latest literature. For example, the topic of transit access to essential services has gained increased attention by researchers.

Moreover, methods to evaluate and improve transit equity are increasingly a topic of interest in literature. A written summary of the literature review is provided in Chapter 2 of this report.

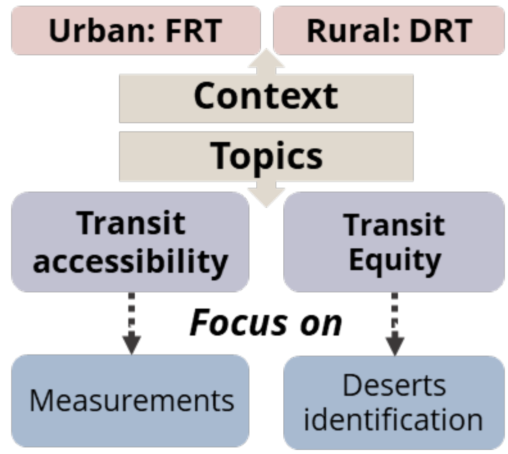
- **Task 2: Collect and clean data on transit, demographics, and essential services**
  The next task involved collecting the most up-to-date data on (1) FRT transit services in Tennessee; (2) demographics; (3) the locations of childcare facilities, food stores, healthcare facilities, school, and parks; and (4) DRT trip data. These datasets were gathered from online public sources or were provided by TDOT. More details on the data is provided in Chapter 3 of this report.
- **Task 3: Analyze spatial transit access to essential services**
  The third task was to measure spatial access via transit to essential services by applying time-based measures that calculated the travel time to access the nearest essential service location via transit. Accessibility measurements were conducted using Conveyal's "Analysis" software for Knoxville, Memphis, Nashville, and Chattanooga. More details on the method used to conduct the spatial analysis of fixed route transit service is provided in Chapter 3 of this report.
- **Task 4: Analyze temporal variation of transit accessibility and propose a spatiotemporal transit supply index**
  The next part of the project evaluated the temporal variation of transit accessibility across four time periods of a day. The statistical temporal variation of transit accessibility was calculated using the open source software tool R. After that, a spatiotemporal transit supply index was calculated that included both the spatial transit accessibility results from Task 3 as well as the temporal variation of transit accessibility; this index is discussed more in Chapter 3 of this report.
- **Task 5: Analyze demand response transit access in a less populated area**
  Task 5 analyzed access of DRT services to essential destinations in a less populated area. This task relied on real-world DRT trip data to measure accessibility; trip data included both the origin location (e.g., home) and the destination location (e.g., a hospital). DRT trip data was already available to the research team for Lakeway Transit in Morristown, TN through a previous TDOT research project RES 2021-03 ("Connecting Demand Response Transit with Fixed Service Transit"). More details on the DRT data and method are provided in Chapter 3 of this report.
- **Task 6: Identify neighborhoods with limited access and propose transit improvements**
  Task 6 compared the transit accessibility results from Task 3 and Task 4 to identify neighborhoods in urban areas that had limited fixed route transit access overall and limited transit access to specific essential services. Then, hypothetical changes to transit service near these locations were evaluated using Conveyal's Analysis tool. The potential transit service changes focused on pragmatic and low-cost modifications, such as adding or changing the location of a bus stop or increasing the frequency of service on an existing route. The results are shown in Chapter 4 of this report.
- **Task 7: Write final report and presentation**
  The final task was writing this report, which summarizes the key findings of this research.

1.4 Structure of the Report

This report is organized as follows. Chapter 2 provides a comprehensive literature review on transit accessibility and transit equity of FRT and DRT. Chapter 3 presents the method and data used to measure transit accessibility of FRT and DRT. Chapter 4 discusses the results of the analysis of spatiotemporal transit accessibility of FRT to essential services in the four major metro areas (Nashville, Knoxville, Chattanooga, Memphis) and potential transit service modifications, as well as the results of DRT accessibility to essential destinations. Chapter 5 includes conclusions, areas for future research, and recommendations. Additional information is included in the Appendices.

Chapter 2 Literature Review

First, literature on the following three topics were reviewed: 1) fixed-route transit accessibility to essential services, 2) transit equity of essential services, 3) DRT accessibility measures and desert identification. The primary search engine used to conduct this review was Google Scholar. Several key terms were used to find relevant journal articles, including transit accessibility, temporal variation of transit accessibility, transit demand, transit equity, essential services, DRT, and transit deserts. This section primarily reviewed studies that were conducted within the United States since these were the most relevant to the study areas in Tennessee.



2.1 Transit accessibility of FRT to essential services

A growing number of studies published in the last decade have focused specifically on accessibility via transit, which refers to one's ability to reach opportunities by taking transit (El-Geneidy et al., 2016; Owen & Murphy, 2020b; Stewart, 2017; Welch, 2013; Yan et al., 2022). The most extensively researched topic in these studies is transit accessibility to jobs (Hess, 2005; Karner, 2018; Kawabata & Shen, 2006; Yan et al., 2022). However, the critical role of accessibility to essential services to improve the quality of life of individuals and evaluate the operational efficiency of transit systems has received less attention in the literature. Some travelers use transit to get to other essential services, such as food stores, healthcare facilities, schools, childcare services, and green spaces. Accessibility to these other essential services that meet the needs of people, especially populations with limited personal vehicles, minority populations or low-income people who rely on transit, is a key consideration for transit planners and stakeholders to evaluate transit equity.

Numerous recent studies have suggested the importance of providing accessible food sources for residents, as a lack of access to affordable and nutritious food has been linked to a range of negative health outcomes and is often indicative of broader systemic issues related to poverty and inequality (USDA, 2023; Walker et al., 2010; Wood & Horner, 2016; Zhang & Mao, 2019). Similarly, prior research focusing on transit accessibility to healthcare has emphasized the significance of such access for vulnerable populations and has highlighted the need for policymakers to take action to enhance transit access to healthcare facilities (Brondeel et al., 2014; Jin et al., 2022; Mao & Nekorchuk, 2013; Zhang et al., 2022).

While food and healthcare are widely recognized as fundamental needs that play a critical role in people's lives, education and childcare services have received comparatively less attention in the literature. One prior study evaluated transit access to schools and found that highly educated people typically have better access to schools than other destinations (Ermagun & Tilahun, 2020). Some studies found that low-income parents frequently rely on transit for childcare trips, suggesting that transit access to childcare should be a significant factor in transit evaluation (Wang & Xu, 2020).

Additionally, parks offer a range of benefits for physical and mental well-being, community building, and environmental sustainability (Park et al., 2021). As such, parks are an important component of a well-functioning city and should not be overlooked in efforts to address service deserts and promote equitable access to essential services. One prior study analyzed transit accessibility levels to parks for disadvantaged populations and suggested that accessibility to parks has an important effect on both human health and social justice (Park et al., 2021).

Last, previous studies have predominantly concentrated on transit accessibility to one specific type of essential service, and only a few prior studies have considered multiple destinations, thereby creating a gap in the literature in which multiple essential service destinations are considered and compared. To address this gap, this study will calculate the transit accessibility to five types of essential services and provide insights into the variations in transit accessibility among these essential service destinations.

2.1.1 Measurement of FRT accessibility to essential services

Transit accessibility measurements can be broadly classified into two categories: opportunity-based (primal) and time/cost-based (dual) measurements (Cui & Levinson, 2020). Opportunity-based measurements rely on predefined travel time thresholds that have no standard value under different scenarios (Levinson & King, 2020). Such measurements are typically used in scenarios where individuals have multiple options, like accessing job opportunities. However, compared to jobs, essential services tend to be fewer in number and more dispersed in distribution. Consequently, prior research commonly employed a time-based approach to measure transit access to these essential services, as it mirrors the actual travel behaviors of accessing essential services. In contrast to the opportunity-based approach, which calculates the number of accessible opportunities within a specified time threshold, time-based measurements assess the travel time required to access a fixed number of opportunities (Cui & Levinson, 2020). This measurement is particularly valuable when the emphasis is on the significance of time in reaching these destinations (Levinson & King, 2020). For instance, travel times between each census block–supermarket pair were converted into measurements of transit accessibility to supermarkets in Cincinnati, Ohio (Farber et al., 2014). This approach has also found successful application in evaluating the accessibility of other essential services, such as a recent study examining healthcare accessibility in Florida (Ghorbanzadeh et al., 2020). Another key advantage of utilizing travel time as the accessibility metric is its capacity to facilitate direct comparisons of transit accessibility levels among different types of essential services and various groups of transit users. Moreover, measuring access in travel time offers a user-friendly and easily interpretable scale, making it more comprehensible to the public (Levinson & King, 2020). Therefore, in this study, the time-based approach is applied in the transit accessibility calculation.

Time-based approach: travel time required to access a fixed number of destinations

2.1.2 Temporal variation of FRT accessibility to essential services

Another important consideration in the analysis of transit accessibility to essential services is the temporal variation caused by differences in departure times or the variation in transit service frequency across different times of the day (Yan et al., 2022; Zhang et al., 2022). A growing body of literature incorporates temporal variation into the calculation of transit accessibility, either by calculating the average accessibility over multiple time windows (Allen, 2019; Boisjoly & El-Geneidy, 2016; Fransen et al., 2015) or by weighting accessibility based on the percentage of time windows that reach a predetermined threshold (Farber et al., 2014). While commuting trips may be more concentrated during the AM and PM peaks on weekdays, trips to access essential services may be more likely to occur at other times of the day (Allen, 2019). Neglecting temporal variations in evaluating transit access to essential services may lead to inaccurate results, potentially resulting in incomplete and inadequate planning for future transit development.

This research first follows the method in previous studies (Allen, 2019; Farber et al., 2014; Fransen et al., 2015; Lei & Church, 2010; Yan et al., 2022; Zhang et al., 2022) in measuring transit accessibility in four time period on weekdays (AM peak during 7-10 a.m., midday during 11 a.m.-3 p.m., PM peak during 4 p.m. – 7 p.m., early-evening during 8 p.m. – 11 p.m.). Then, time variation is calculated based on the variance of transit accessibility over these different time periods. Based on the time variance, one previous study that evaluated transit services categorized traffic analysis zones into different scenarios based on the temporal dynamics of transit accessibility (Yan et al., 2022). This previous study also argued that consistently high accessibility throughout the day (i.e., high accessibility with low variance) is a more favorable scenario than a situation with generally high accessibility but occasional sharp drops (i.e., high accessibility with high variance) (Yan et al., 2022). Building on this prior research, this study proposes a comprehensive spatiotemporal transit supply index that weights transit accessibility by the effects of temporal variations on transit accessibility observed within the study area.

2.2 Transit equity of FRT

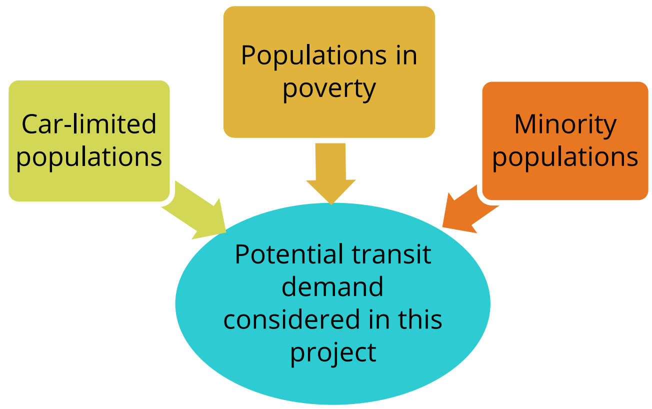
2.2.1 Transit demand

An important step in evaluating transit equity is to identify disadvantaged groups that may have a higher need for transit than the general population. Socially disadvantaged groups typically have less access to resources and goods than the general population and thus are commonly considered in measuring a variety of equity issues (Townsend et al., 1988). Social indicators, which have been widely used to identify socially disadvantaged groups in prior research (Foth et al., 2013; Sánchez-Cantalejo et al., 2008; Townsend et al., 1988), have been extensively applied in transit equity studies (El-Geneidy et al., 2016a; El-Geneidy et al., 2016b; Foth et al., 2013).

In terms of specific indicators, many prior studies have found that individuals with limited access to vehicles are more likely to rely on public transit to meet their transportation needs (Steiss, 2006). In recognition of this relationship, the U.S. Department of Transportation developed a formula for measuring the car-limited population based on data regarding household drivers and vehicle ownership (Steiss, 2006). This formula has subsequently been employed by numerous studies focused on transit equity as a means of quantifying the need for transit (Cai et al., 2020; Jiao, 2017; Jiao & Dillivan, 2013; Lee et al., 2021; Li & Fan, 2020).

Among demographic variables, low-income and minority populations are frequently identified as groups with a higher potential need for transit because they may not be able to afford vehicles. Previous studies (El-Geneidy et al., 2016b; Ermagun & Tilahun, 2020; Foth et al., 2013) suggested that individuals with lower incomes may find the cost of owning and operating a vehicle prohibitive and are therefore more likely to use public transit when it is available (Martens et al., 2019; Taylor & Morris, 2014). Race or ethnicity is often considered as a potential factor because some minority groups may have relatively lower income levels and experience lower levels of car ownership, leading to increased reliance on transit (Di Ciommo & Shiftan, 2017; Lucas et al., 2016; McCray & Brais, 2007).

Last, one prior study specifically conducted in Tennessee indicated that transit riders in Tennessee are more likely to belong to minority groups, have lower income levels, and possess fewer or no personal vehicles (Yang & Cherry, 2017). Therefore, this study will consider potential car-limited populations with limited personal vehicle access, low income levels, and minority populations for the transit equity analysis that follows.

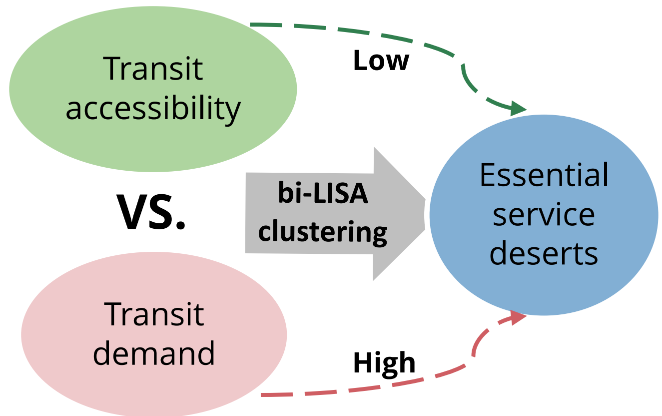


2.2.2 Transit equity of essential services

Previous studies examining transit equity to essential services have yielded varied findings. For instance, one transit equity study conducted in the Detroit Metropolitan Region demonstrated that minority and low-income households had favorable levels of transit accessibility to hospitals, yet faced disadvantages in accessing supermarkets (Grengs, 2015). In another study conducted in Chicago, it was found that low-income households encountered restricted transit accessibility to grocery stores, while the Hispanic population experienced increased transit accessibility to grocery stores but faced limitations in accessing hospitals (Ermagun & Tilahun, 2020). Notably, these studies focused on dense areas with well-established transit networks. Therefore, the following analysis conducted in Tennessee provides a valuable addition to the existing literature by examining the transit equity of essential services specifically in lower-density urban areas with primarily bus-based transit systems.

The term "transit desert" has been extensively discussed in prior literature and is generally defined as geographic areas or locations that have high transit demand and limited transit accessibility; this term can be extended to a specific type of service, such as "food deserts" (Forsyth et al., 2010; Walker et al., 2010) and "healthcare deserts" (Brondeel et al., 2014; Jiao & Dillivan, 2013; Mao & Nekorchuk, 2013). However, few prior studies have quantified transit equity for accessing multiple essential services that are important to fulfill people's many fundamental needs (Cui & Levinson, 2020; Zheng et al., 2019). Therefore, the concept of "essential service deserts" is proposed in this paper to identify areas with limited access to numerous essential services.

The literature on transit equity typically employs comparative or statistical approaches to measure transit equity. Comparative approaches include simple gap identification methods to identify transit deserts by the difference or ratio of supply and demand (Aman & Smith-Colin, 2020; Jiao, 2017; Jiao & Dillivan, 2013). In terms of statistical approaches, various indicators have been used to quantify transit equity, such as the Gini coefficient (Liang et al., 2023) and the Theil index (Jin et al., 2022). Some studies involving spatial analysis of transit equity have utilized the bivariate local indicator of spatial association (bi-LISA) to evaluate the spatial disparity of the relationship between transit supply and demand (Jin et al., 2022; Liang et al., 2023), which is the approach that will be used in this research.



Despite numerous prior studies conducted on transit equity analysis, few – if any – of the prior studies have considered the spatial inequity of transit with regard to different types of essential services and the potential spatial correlations between different essential service deserts. This highlights the need for further research to consider the interconnectivity between transit accessibility and essential service facilities in order to better understand the spatial patterns of transit inequity.

2.3 DRT accessibility measures and desert identification

This section briefly discusses relevant literature pertaining to transit accessibility measures and transit desert identification, as well as their applicability to DRT.

2.2.1 DRT accessibility

Transit accessibility refers to the ability to reach trip destinations via transit (Manout et al., 2018). An increasing number of studies published in the last decade have focused on transit accessibility for fixed route transit systems (El-Geneidy et al., 2016b; Owen & Murphy, 2020; Stewart, 2017; Welch, 2013; Wessel & Farber, 2019). However, there is a noticeable research gap in accessibility analysis for DRT.

Previous studies mostly relied on two types of metrics—travel costs or cumulative opportunities—to measure accessibility (Cui & Levinson, 2020). In addition to these metrics, there are different approaches for implementing accessibility measurements. In the literature on transit accessibility, one of the most significant differences exists between studies based on *potential accessibility* and *actual accessibility* (Niedzielski & Boschmann, 2014). Calculating potential accessibility requires making assumptions about travel behavior, such as travel thresholds or preferences for destinations. This approach is often used in situations where there is no reference to actual travel behavior (Niedzielski & Boschmann, 2014). Actual accessibility, on the other hand, is measured by the actual travel distance or travel time directly (Niedzielski & Boschmann, 2014).

In this study, DRT accessibility will be quantified as the travel distance that was recorded in real-world DRT trip data. The use of actual travel distance from DRT trip data ensures the repeatability of the methodology across DRT systems in other areas.

DRT accessibility

Travel distance measure: average trip distance to access different essential destinations

2.2.2 Desert identification

The term "transit desert" has been extensively discussed in prior literature and is generally defined as geographic areas or locations that have high (fixed route) transit demand and limited (fixed route) transit accessibility (Brondeel et al., 2014; Forsyth et al., 2010; Jiao & Dillivan, 2013; Mao & Nekorchuk, 2013; Walker et al., 2010). The concept of transit deserts can be used to identify areas of concern by analyzing the relationship between transit demand and transit accessibility to important destinations (Aman & Smith-Colin, 2020; Jiao, 2017; Jiao & Dillivan, 2013; Ricciardi et al., 2015).

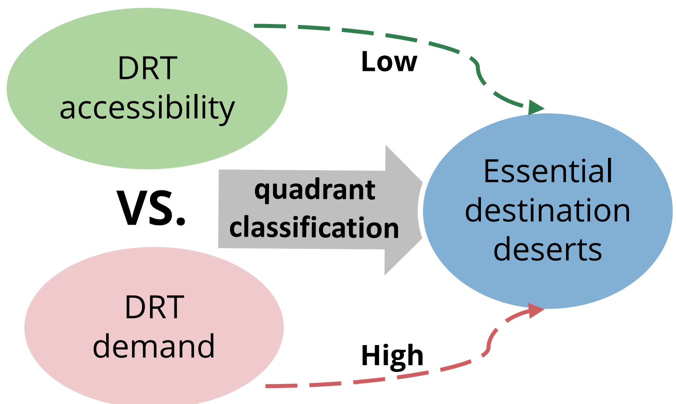
Transit demand is usually defined as groups characterized by higher utilization of transit services or disadvantaged individuals who may rely on transit due to limited access to personal vehicles (El-Geneidy et al., 2016a; El-Geneidy et al., 2016b; Foth et al., 2013; Guo et al., 2023; Jeddi Yeganeh et al., 2018). In this study, DRT demand analysis will include total DRT demand, female DRT demand, and elderly DRT demand; this will be quantified as the count of DRT trips made by total passengers, female passengers, and the elderly, respectively. This study specifically examined female and elderly demographic groups due to the availability of age and gender information in the recorded DRT trip data, as well as the recognition that women and the elderly make up a substantial proportion of DRT riders in the study area.

DRT demand

Count of DRT trips made by total passengers, female, and the elderly

Previous studies identifying transit deserts also evaluated transit accessibility to various types of important destinations (e.g., jobs, food stores, healthcare, etc.) for different demand groups, such as the previously mentioned study of Detroit (Grengs, 2015) and Chicago (Ermagun & Tilahun, 2020). Moreover, previous studies on transit deserts commonly identified geographic areas or locations that have limited transit accessibility to different types of destinations, such as "*food deserts*" (Forsyth et al., 2010; Walker et al., 2010) and "*healthcare deserts*" (Brondeel et al., 2014; Jiao & Dillivan, 2013; Mao & Nekorchuk, 2013). However, these studies have primarily focused on large urban areas with well-established fixed-route transit networks. Therefore, the following analysis in a small urban area contributes to the literature by examining "essential destination" deserts in a less populated area with widespread destinations and limited public transit alternatives.

Based on the prior literature on transit deserts, there are different methods to understand the relationship between transit demand and transit accessibility to identify areas of concern. For example, some studies identified transit deserts by using the difference or ratio of demand and accessibility (Aman & Smith-Colin, 2020; Jiao, 2017; Jiao & Dillivan, 2013). In another study, areas with high public transit demand but limited public transit accessibility were evaluated using a quadrant classification method, which categorized regions into four classes based on their levels of transit demand and accessibility (Ricciardi et al., 2015). This classification method proved to be relatively simple to construct yet highly effective in producing meaningful outcomes (Ricciardi et al., 2015). Furthermore, it was easily comprehensible and feasible for transit agencies and policymakers to employ. Therefore, the proposed "essential destination" deserts analysis will employ a quadrant classification to spatially identify potential areas of concern with high DRT demand and limited DRT accessibility.



Chapter 3 Data and methodology

This section discusses the data and methods used in this study, beginning with the fixed route transit (FRT) analysis.

3.1 Data for FRT analysis in Nashville, Memphis, Chattanooga, and Knoxville

This section discusses the data used to measure transit accessibility and transit equity to essential services via FRT in Nashville, Memphis, Chattanooga, and Knoxville. General Transit Feed Specification (GTFS) data including static transit schedules and geospatial transit networks for 2023 were collected from the Nashville Metropolitan Transit Authority (WeGo Transit), Memphis Area Transit Authority (MATA), Chattanooga Area Regional Transportation Authority (CARTA), and Knoxville Area Transit (KAT). For the transit accessibility calculations, origin locations were the centroid of each Census block; the 2020 TIGER/Line shapefile of Census blocks and Census block groups were obtained from the U.S. Census Bureau (U.S. Census Bureau, 2020). The Census block level was aggregated to the Census block group level to evaluate transit equity. The demographic information used to estimate the potential demand for transit was downloaded at the Census block group level from the U.S. Census Bureau (U.S. Census Bureau, 2020).

Location data for essential services, including food stores, healthcare facilities, schools, childcare facilities, and parks, were assembled from various online datasets. These sources are from nationally available programs such as the Supplemental Nutrition Assistance Program (SNAP), the Department of Homeland Security (DHS), National Center for Education Statistics (NCES), and The Trust for Public Land. A description of these datasets is shown in Table 1.

Last, since the entrance locations of parks were not available from the Trust for Public Land, the locations of park entrances were estimated by the intersection of park boundaries and roads using OpenStreetMap with no restriction to pedestrians, and to ensure the road intercepts the park boundaries, a 100-ft (30.48-meter) buffer was created. The 100-foot (30.48-meter) buffer was implemented based on insights derived from a prior study. This considered the potential for the road centerline to not align precisely with a park boundary, even when they are spatially close enough, along with the possible existence of pedestrian pathways between them, which are not included in the TIGER/Line® shapefiles (Park et al., 2021).

Table 1 Data sources and data descriptions

Data	Categories	Data source	Data description
Transit information	GTFS	WeGo transit, MATA, CARTA, KAT	Transit schedule, routes
Geographic information	TIGER/Line Shapefile	U.S. Census Bureau	2020 TIGER/Line shapefile of census block and census block group boundaries
Demographic information	Car-limited population	U.S. Census Bureau	2021 ACS data: Household Type (Including Living Alone) by Relationship; Tenure by Vehicles Available; Sex by Age
	Poverty population	U.S. Census Bureau	2021 ACS data: Ratio of Income to Poverty Level in the Past 12 Months
	Minority (Race and ethnicity) population	U.S. Census Bureau	2021 ACS data: Race; Hispanic or Latino Origin by Race
Essential service facility locations	Food stores	Supplemental Nutrition Assistance Program (SNAP) from the U.S. Department of Agriculture (USDA)	The locations of food stores were exported from SNAP the USDA website. An interactive mapping program on the USDA website provides a GIS dataset of authorized SNAP retailers including supermarkets, grocery stores, and convenience stores.
	Healthcare facilities	Department of Homeland Security (DHS)	The locations of healthcare facilities including hospitals were exported from the Homeland Infrastructure Foundation-Level Data (HIFLD) Open Data website provided by DHS.
	Schools	National Center for Education Statistics (NCES)	GIS datasets for educational institutions including colleges, universities, and public and private elementary and secondary schools were downloaded from the NCES Edge Open Data website.
	Childcare facilities	Department of Homeland Security (DHS)	A list of childcare services in the State of Tennessee was downloaded through an interactive tool from the Homeland Infrastructure Foundation-Level Data (HIFLD) Open Data website provided by DHS.
	Parks	ParkServe® data (The Trust for Public Land, 2019)	A list of parks that have open access (no restricted access)

3.2 Data for DRT analysis in Morristown

3.2.1 DRT study area

The study area focused on the small city of Morristown, which is in Hamblen County located within the eastern region of Tennessee. Morristown is primarily characterized as an automobile-dependent, small city with limited public transportation options. Currently, Lakeway Transit operates three bus routes within the city, deploying only four vehicles for fixed route services (Lakeway Transit, 2023). These services are available from Monday to Friday until 6 p.m. In addition to the bus routes, Morristown has demand response transit (DRT) services facilitated by the East Tennessee Human Resource Agency (ETHRA) Public Transit. These DRT services aim to address the transportation needs of the community in a more flexible and on-demand manner. ETHRA Public Transit offers door-to-door transportation service to the general public, available through advanced reservations. The cost for a one-way trip is $3, and trips crossing county lines incur an additional $3 fee. **Figure 1** shows the geographic location of Morristown, accompanied by a map of the origins and destination points of the DRT trip data used in this paper and discussed in the subsequent section.

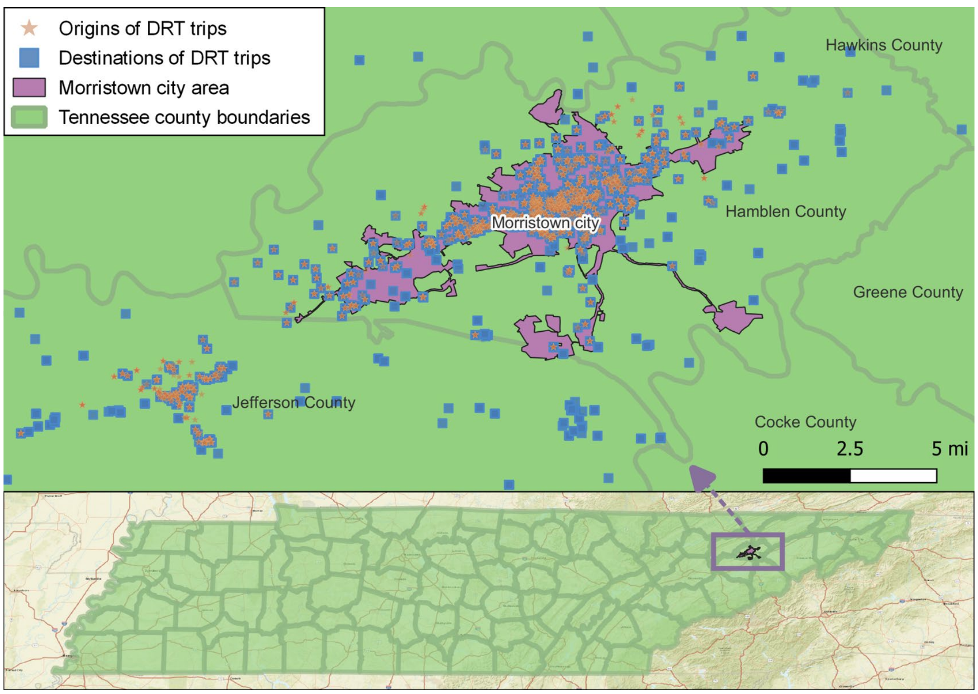


Figure 1 Study area and the origins and destinations of DRT trips in Morristown

The DRT trips from Morristown, collected from 2019 July to 2020 June, were obtained from ticket data from the East Tennessee Human Resource Agency (ETHRA) Public Transit reservation system. This system recorded the origins and destinations of passengers and the start time of the trip. The data was selectively filtered, retaining only the origin points situated within Hamblen County and its adjacent area, Jefferson County for the following analysis. The data was then cleaned to remove outliers. For example, two observations were flagged as temporal abnormalities because the trips occurred at the unusual hour of 2 a.m. and were therefore removed from the dataset. Regarding spatial abnormalities, a total of 16 observations were identified as having incorrect coordinates, as they were spatially mapped to locations outside of the state boundary. This inaccuracy primarily arose from ambiguous street addresses where multiple locations within the United States shared identical street names. To ensure precision, a meticulous geocoding process was employed to reassign the coordinates by incorporating comprehensive addresses, including zip codes. The data cleaning process was able to rectify the spatial locations of these observations and guarantee the integrity of the data.

The original dataset included 31,641 DRT trip records. Records that had no gender information (6,333 records), as well as those with blank or negative age information (6,501 records), were excluded from the analysis. Following the data-cleaning process, a total of 22,669 trip records were retained for analysis. Based on the cleaned data, several categorical variables were created for further analysis. The variable creation and explanation are shown in **Table 2** included in Appendix 1.

3.2.2 Identification of DRT trip purposes

A heatmap showing the count and proportion of trips to/from varying origin and destination types in the initial DRT trip data is included in **Figure 39** in Appendix 1. The intensity of the green color indicates the percentage of trips, with a darker hue representing a higher percentage. It can be inferred from **Figure 39** that trips predominantly originated from or terminated at the residential locations of clients. Specifically, trips made from clients' residences to employment areas are the most prevalent, closely followed by trips from physicians' locations to the residences of clients. Empty cells in the figure indicate the absence of trips linked to certain types of locations as origins or destinations. For instance, journeys starting from schools primarily terminated at clients' residences, with the destinations also including shopping locations and others; however, only one trip was recorded for each of these.

DRT trips were then classified using a method typically employed in transportation planning and modeling, and the trip classification results are provided in **Table 3** in Appendix 1. Specifically, trips between home and work were classified as Home-Based Work (HBW); trips with one end at home and one end not related to work were classified as Home-Based Other (HBO); and trips that did not originate from or terminate at a home location were classified as Non-Home-Based (NHB). These classifications were further divided into several distinct trip purposes based on the origin land use types and destination land use types. Specifically, locations such as hospitals, pharmacies, physicians, and dialysis centers were categorized as healthcare locations. Consequently, trips that either originated from or terminated at client residences to these locations were classified as Home-Healthcare trip purposes. Conversely, trips originating from locations other than client residences to these healthcare locations were categorized as non-Home-Healthcare trip purposes. Similar classifications were observed with trips involving government services and banks, identified as either Home-Service or non-Home-Service trip purposes. Additionally, trips involving shopping locations and churches fell into the Home- or Non-Home-Leisure trip purpose category. The types and trip purpose, along with explanations for each classification, are presented in Table 3 in Appendix 1.

Table 3 in Appendix 1 reveals that the HBO category was the most common, with Home-Healthcare trips accounting for the highest count. The second most prevalent category was the Home-Work trip purpose, falling under the HBW trip type. However, NHB trips contributed a relatively small count, accounting for 996 out of a total of 22,669 trips, approximately 4.4%. As a result, the subsequent analysis excluded the NHB category, focusing solely on home-based trips (both HBO and HBW). This decision was due to the limited number of observations in the NHB category, which could lead to inadequate variability.

3.3 Methodology for FRT analysis in Nashville, Memphis, Chattanooga, and Knoxville

This study proposed a five-step method shown in **Figure 2,** which provides a framework for the FRT analysis. In the first step, a spatiotemporal transit supply index was developed to incorporate travel time-based transit accessibility and the temporal variation of accessibility across different times of the day. The next step involved the creation of a demand index for three potential groups that historically rely on transit utilizing sociodemographic data obtained from the U.S. Census Bureau. To identify areas with limited transit access to essential services, the last step investigated the spatial disparity of the relationship between transit supply to access different essential services and potential transit demand using the bivariate local indicator of spatial association (bi-LISA). Each of these steps is described in more detail in the following section.

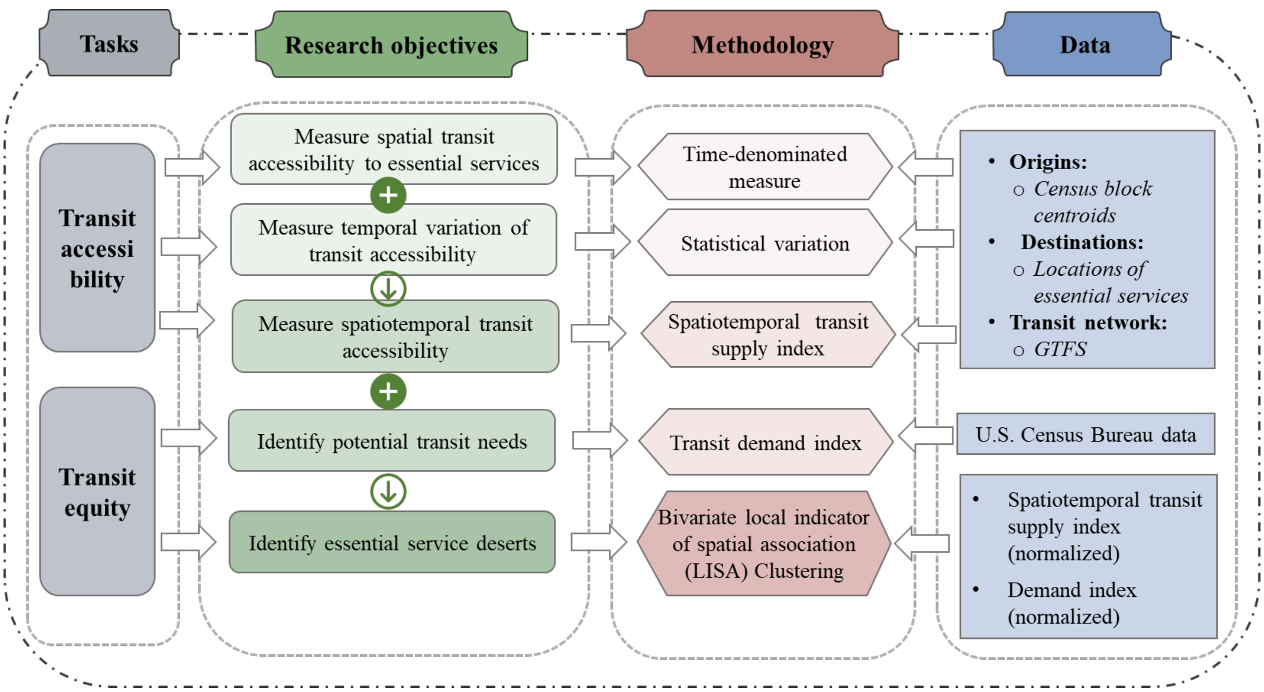


Figure 2 Conceptual framework for FRT analysis

3.3.1 Step 1: Measure spatial transit accessibility

A time-based measurement was used to calculate the travel time required for accessing the nearest essential service facility via transit at a given departure time point. This method assumes that users opt for the nearest essential service location due to the unavailability of actual travel behavior data showing essential service selection. The calculation of transit travel time was done in the Conveyal Analysis platform. The transit travel time includes walking time to access and egress from transit stops, waiting time at the stop, and in-vehicle travel time. In the Conveyal Analysis platform, the maximum walking time was set at 20 minutes, the walking route followed the street network developed by OpenStreetMap, and a maximum of three transfers were assumed. In addition, a time percentile needs to be selected to represent the arrival process of riders at the stop based on transit schedules. A lower percentile indicates that riders are accustomed to relying on schedules and that they adjust their departure time to minimize waiting times at the stop and overall travel times, which often is the case in areas with less frequent service. A higher percentile suggests that riders are less reliant on schedules, potentially starting trips randomly, which is typical in areas with high-frequency transit service. In this study, the time percentile was set at the median (50th percentile), which represents a mix of both timed arrivals and random arrivals at the transit stop. The equation for calculating the travel time is shown in **Equation (1)**.

$$Transit\_access_{ijT} = \min_{\forall k \in K, \forall t \in T} (Travel\_time_{ijtk}) \quad (1)$$

Where:

$Travel\_time_{ijtk}$ is the travel time via transit from the block centroid i to the k^{th} location of the essential service j at departure time t;

k is the location of essential service j;

j is the type of essential service facility including food stores, healthcare facilities, schools, childcare facilities, and park entrances;

t is the departure time within the time window T.

Time windows include the AM peak during 7:00 - 9:59, midday during 11:00 - 13:59, PM peak during 16:00– 18:59, and early evening during 19:00 - 21:59 on a weekday. Therefore, $Transit\_access_{ijt}$ is the minimum transit travel time needed to travel from origin i to the nearest essential service facility j at time window T. Then the average transit accessibility for a day is calculated using **Equation (2)**.

$$Transit\_access_{ij} = \frac{\sum_T Transit\_access_{ijT}}{Number\ \ of\ T} \quad (2)$$

Where $Transit\_access_{ij}$ is the average travel time from the block centroid i to the essential service facility j and T is equal to 4.

3.3.2 Step 2: Measure time variation of transit accessibility

The time variation of transit accessibility is calculated using **Equation (3)**.

$$\mathrm{Time\_Variation}_{ij} = \frac{\sum_T (Transit\_access_{ijT} - Transit\_access_{ij})^2}{(Number\ \ of\ T)-1} \quad (3)$$

Where T represents time windows and $\mathrm{Time\_Variation}_{ij}$ is the time variation from the block centroid i to the essential service facility j.

3.3.3 Step 3: Measure transit supply index

Equation (4) was developed to measure the spatiotemporal transit supply index, which assigns weights to travel time-based transit accessibility. First, the travel time-based transit accessibility was normalized to a range of 0 to 1. For ease of interpretation and consistency with common conventions, the transformation represented as one minus the normalized travel time-based transit accessibility, was employed. This transformation ensures that a higher transit supply index value corresponds to a larger value level of accessibility and lower values show worsening access. The assignment of weights was determined by the effects of temporal variations on transit accessibility observed within the study area.

$$Transit\_supply_{i,j} = \left(1 - [Transit\_access_{ij}]_{\boldsymbol{normalized}}\right) * Weight_{i,j} \quad (4)$$

Where:

$$[Transit\_access_{i,j}]_{\boldsymbol{normalized}} = \frac{(Transit\_access_{i,j} - \min(Transit\_access_j))}{(\max(Transit\_access_j) - \min(Transit\_access_j))};$$

$Transit\_supply_{i,j}$ is the transit supply to access the essential service facility j for the block i;

$Weight_{i,j}$ represents the weight that is determined based on the temporal variation of transit accessibility to the essential service facility j for the block i.

The next step is to determine the weights; this section uses the example of Nashville to illustrate the measurement process. First, the distribution of the results in the study area from the previous two steps (step 1 and step 2) were visualized through scatter plots and box plots (as illustrated in **Figure 3**). The x-axis denotes the average transit accessibility represented by the average travel time in minutes, and the y-axis denotes the temporal variation of transit accessibility. The blue box plots provide a summary of average transit accessibility, and the pink box plots depict a summary of the temporal variation of transit accessibility. Additionally, the orange box plots display the distribution of non-zero temporal variation of transit accessibility. As can be seen in **Figure 3**, the pink box plots generally have narrow boxes and short whiskers that extend toward the lower end of the plots, which suggests that the majority of the data points have values near zero. This indicates that the time variation of transit accessibility across the four time periods is minimal, suggesting that most transit services maintain a consistent schedule across different time periods. Therefore, the time variation value of zero was categorized as low variation. For those cases with time variation value greater than zero, time variation was categorized into low and high variation based on the third quantile value instead of the median value (the third quantile value was computed after separating zero-time variation cases). The transit accessibility results were categorized based on the quantile threshold values into four categories, namely high transit accessibility (travel time less than the first quantile), moderate-high transit accessibility (travel time ranging from the first quantile to the median), moderate-low transit accessibility (travel time ranging from the median to the third quantile), and low transit accessibility (travel time greater than the third quantile). The scatter plots and box plots of travel time and time variation in the other three cities can be found in Appendix 2.

Then, weights were proposed for various combinations of transit accessibility and time variation, as illustrated in **Figure 4**. The highest weight was assigned to areas with high transit accessibility and low variation, indicating consistently high transit accessibility and the highest level of the transit supply index. The second-highest weight was assigned to areas with high transit accessibility and high variation, indicating overall high transit accessibility with occasional dips in accessibility. Conversely, the lowest weight was assigned to areas with low transit accessibility and low variation, indicating consistently low transit accessibility and the lowest level of the transit supply index. The second-lowest weight was assigned to areas with low transit accessibility and high variation, indicating overall low transit accessibility with occasional increases in accessibility. Consequently, six weights were assigned with a linear progression from 1/6 to 1 (Fransen et al., 2015). This progression guarantees that the transit supply index falls within the range of 0 to 1, offering a meaningful scale for interpretation while also facilitating a comprehensive spatiotemporal assessment of transit supply to access essential services.

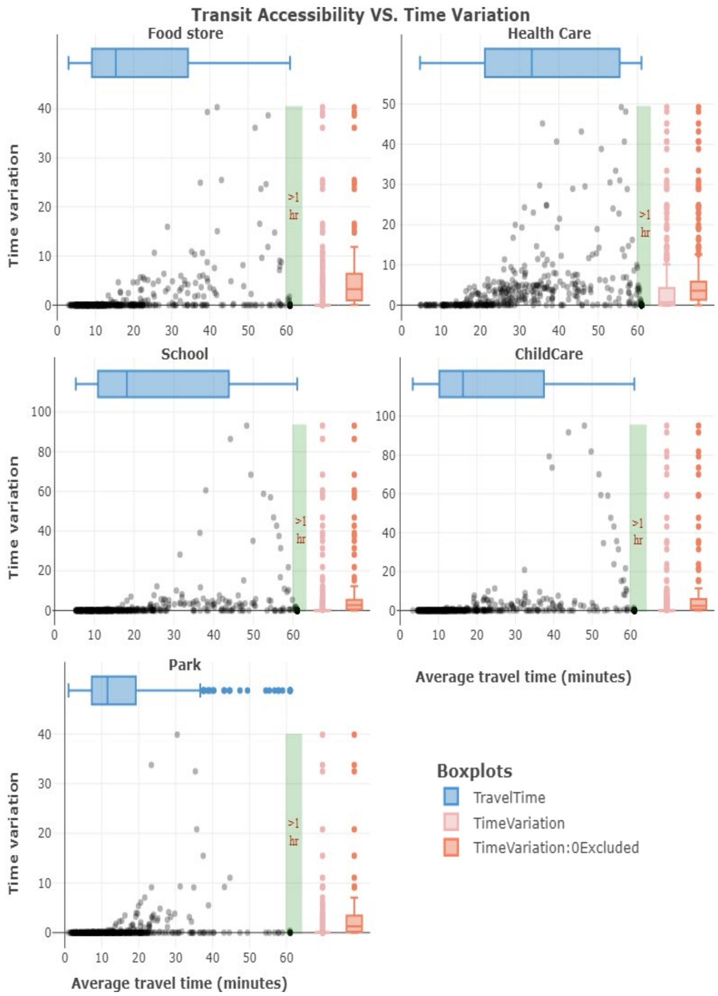


Figure 3 Scatter plots and box plots of transit accessibility and time variation in Nashville

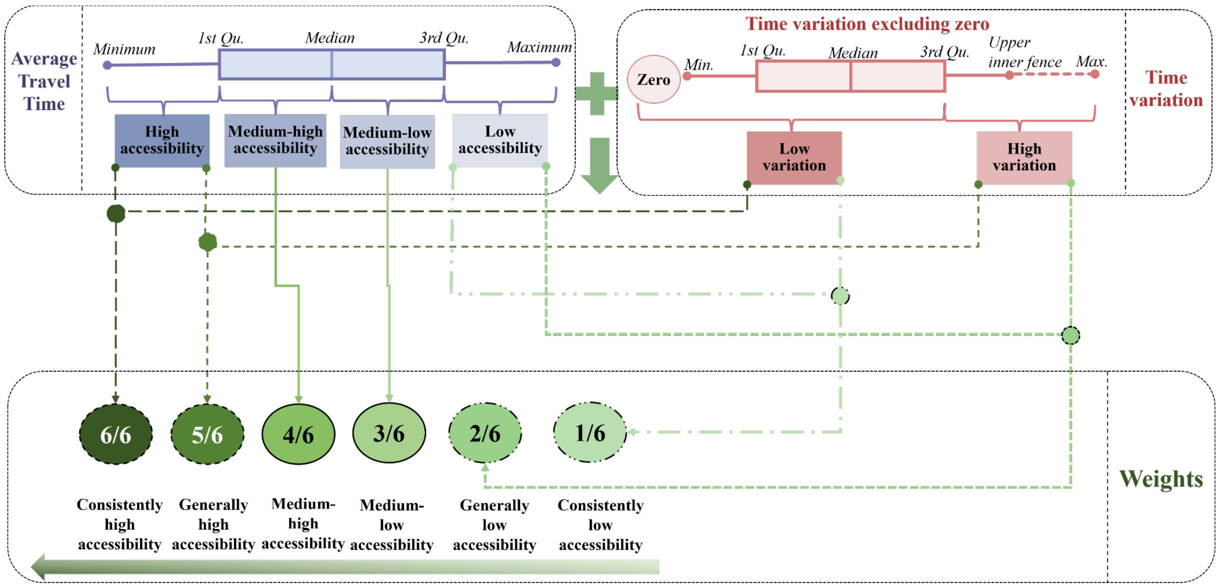


Figure 4 Proposed weights for the estimation of spatiotemporal transit supply to access essential services

3.3.4 Step 4: Measure transit demand index

Drawing on prior research, three sociodemographic groups were selected for evaluation in Step 4 of the method. The first group was car-limited populations, and the formula for this was adapted from research conducted by the U.S. Department of Transportation (USDOT) (Steiss, 2006). Car-limited populations were identified as those individuals who are unable to operate a vehicle or have limited vehicles available to use and, consequently, are more likely to rely on transit for their daily transportation needs. It is noted that individuals living in group quarters were deducted from the car-limited population calculation formula because the entity or organization that owns or manages the group quarters provides housing and/or other services for the residents (U.S. Census Bureau, 2021a), which may affect their reliance on transit.

Based on the USDOT formula, prior studies further considered potential car-limited populations who are not able to drive but sometimes might need to go out on their own (Jiao, 2017; Jiao & Dillivan, 2013; Li & Fan, 2020). This research utilized the formula adapted from a previous study (Li & Fan, 2020) that included the population aged 10-15 as potentially car-limited. It is important to note that while there is no universal legal age at which children may be allowed to travel independently, the Tennessee State Courts (Tennessee State Courts) recommend against leaving children under the age of 10 unattended.

Accordingly, **Equation (5)** to **Equation (7)** were developed for this research to calculate the car-limited index at the i_{th} census block group:

$$Driving - age\_population_i = (populations\ over\ age\ 16)_i - (people\ living\ in\ group\ quarters)_i \quad (5)$$

$$Car - limited\_population_i = (Driving\ age\ population)_i - (Number\ of\ available\ vehicles)_i + (Total\ population\ between\ 10 - 15)_i \quad (6)$$

$$Car - limited\_index_i = [Car - limited\_population_i\ ]_{\boldsymbol{normalized}} \quad (7)$$

The normalization process in **Equation (7)** followed the same min-max method as applied in **Equation (4)**.

Before continuing, it should be noted that a lack of data specifically showing the difference in the number of drivers and available vehicles at the household level may potentially result in an underestimation of the need for transit.

The remaining two potential transit demand groups are comprised of poverty and minority populations, which are recognized as protected groups entitled to equitable transit access under Title VI of the Civil Rights Act of 1964. Poverty is defined as individuals with incomes below the poverty threshold (U.S. Census Bureau) at the Census block group level, and minority populations encompass nonwhite and Hispanic origin populations at the Census block group level. Accordingly, **Equations (8) to (9)** and **Equations (10) to (11)** were developed for this study to calculate indexes for the population in poverty and minority populations at the i_{th} Census block group, respectively.

$$Poverty\_population_i = population\ below\ poverty\ threshold_i \tag{8}$$

$$Poverty\_index_i = [Poverty\_population_i\ ]_{\boldsymbol{normalized}} \tag{9}$$

$$Minority\_population_i = \big(NonWhite\ population\ (Black, Asian, American\ Indian, Alaskan)\big)_i + (\ Hispanic\ origin\ population_i\ ) \tag{10}$$

$$Minority\_index_i = [Minority\_population_i\ ]_{\boldsymbol{normalized}} \tag{11}$$

Last, the populations from these three groups were then summed to measure the combined potential transit demand, as shown in Equation (12). All demand indexes had a range of 0 to 1.

$$Combined\ transit\ demand\ index_i = (Car - limited\_population_i\ + Poverty\_population_i\ + Minority\_population_i)_{\boldsymbol{normalized}} \tag{12}$$

The normalization process in **Equation (9), Equation (11), and Equation (12)** followed the same min-max method as applied in **Equation (4)**. According to the findings of prior research (Grengs, 2001; Li & Fan, 2020), it is pertinent to note that due to the inherent overlapping characteristics present in Census data across these demographic factors, there is a potential for unavoidably double-counting some people when aggregating to the combined transit demand index.

3.3.5 Step 5: Identify essential service deserts using bi-LISA

To identify essential service deserts characterized by low transit supply and high potential transit demand, the bivariate local indicator of spatial association (bi-LISA) was utilized to evaluate the spatial disparity of the relationship between transit supply to access essential services and transit demand across Census block groups and to identify spatial clustering of transit inequity. The bi-LISA calculates the local Moran's *I* statistic for each Census block group i, as shown below in **Equation (13)**:

$$I_i = D_i \sum_j W_{ij} S_j \tag{13}$$

Where:

D_i is the standardized transit demand index (*standardization of demand index obtained from **Equation (9), Equation (11), and Equation (12)***) for the Census block group i;

S_j is the standardized transit supply index (*standardization of supply index obtained from* ***Equation (4)***) for the Census block group j;

W_{ij} are the elements of the neighborhood weight matrix that was generated by queen contiguity weight to assess the spatial relationship between Census block group i and Census block group j in which W_{ij} = 1 if i and j are neighbors; W_{ij} = 0 if i and j are not neighbors.

D_i and S_j represent the standardized index, which can encompass both positive and negative values. Consequently, the values for the local Moran's *I* range between – 1 and 1, where positive values represent positive spatial association patterns and negative values indicate the opposite direction. The absolute values of the local Moran's *I* correspond to the strength of the spatial correlation. A 5% significance level was used to determine the statistical significance of the calculation, with Census block groups having a p-value above this threshold considered not significant. The outputs of this step included the bi-LISA clustering maps showing the local spatial correlation patterns for different demand groups and different transit supply categories. The spatial correlation patterns can help to identify the spatial match and mismatch between transit demand and transit supply to access essential services by categorizing the census block groups into four clusters: High-High clusters (Census block groups with high potential transit demand and high transit supply to access essential services), High-Low clusters (Census block groups with high potential transit demand and low transit supply to access essential services), Low-High clusters (Census block groups with low potential transit demand and high transit supply to access essential services), and Low-Low clusters (Census block groups with low potential transit demand and low transit supply to access essential services). Specifically, High-Low clusters were identified as ***essential service deserts***.

3.4 Methodology for DRT analysis in Morristown

This section describes the method used for the DRT analysis in this study. **Figure 5** shows the conceptual framework. The analysis includes three objectives: evaluate DRT trip demand, measure DRT accessibility, and identify potential "essential destination" deserts.

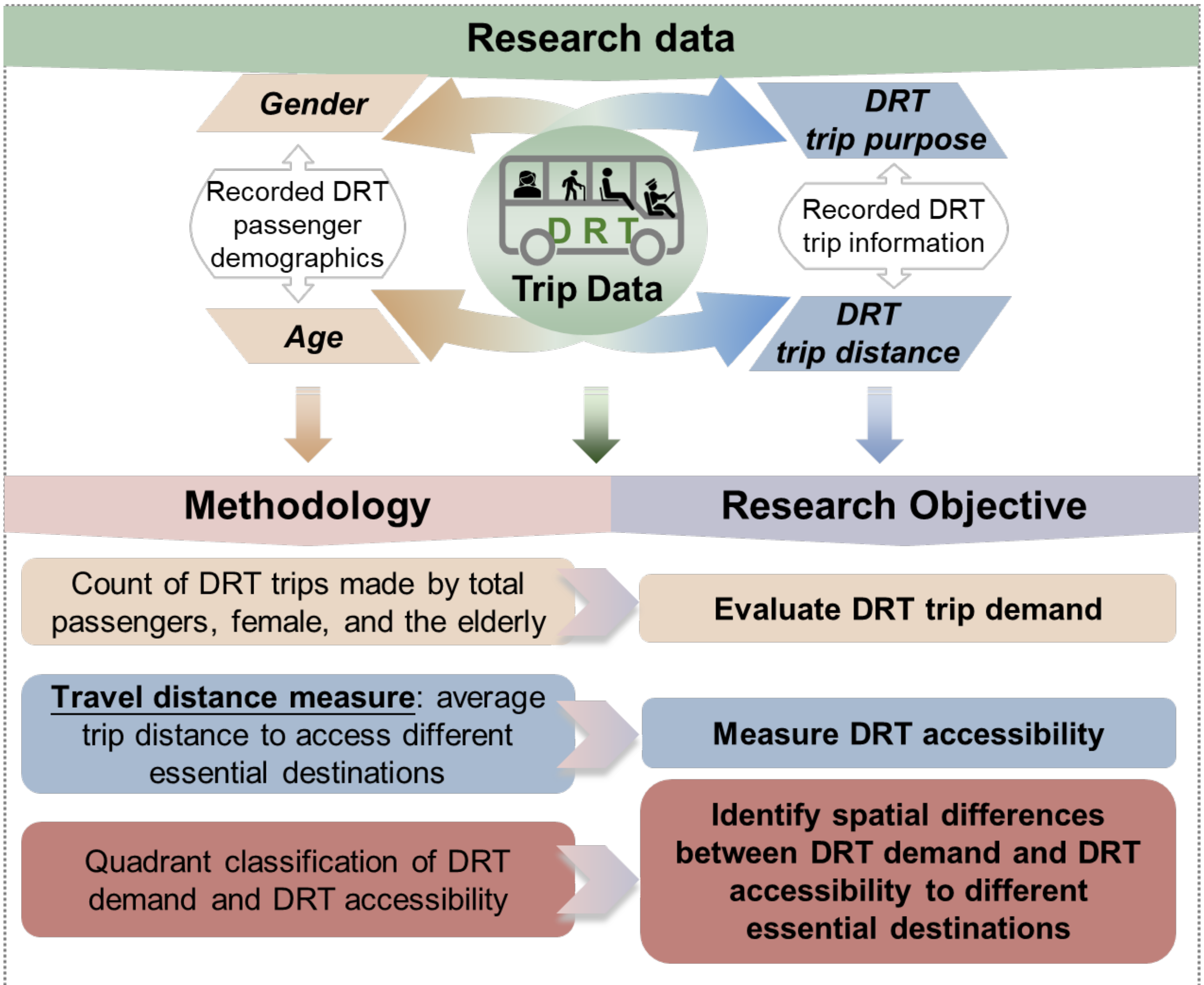


Figure 5 Conceptual framework for DRT analysis

In this report, a spatial analysis was conducted to identify differences between DRT demand and DRT accessibility. It is noted that only home-origin DRT trips were included in the spatial analysis. The focus on home-origin trips was primarily driven by the need to illustrate the spatial distribution of DRT trip demand. By mapping out trips originating from individuals' residences, this study can gain valuable insights into the geographic distribution of DRT trips and identify areas with high demand. The following spatial analysis was performed at the geographical level of Census blocks.

First, the DRT demand within the i_{th} Census block was calculated by summing the total count of DRT trips originating from that block, as shown in **Equation (14)**.

$$Total\_demand_i = number\ of\ total\ DRT\ trips_i \tag{14}$$

In addition to the total DRT demand, the number of DRT trips made by females and the elderly were calculated separately, as shown in **Equation (15)** and **Equation (16),** respectively.

$$Female\_demand_i \ = \ number\ of\ DRT\ trips\ made\ by\ female_i \tag{15}$$

$$Elderly\_demand_i \ = \ number\ of\ DRT\ trips\ made\ by\ the\ elderly_i \tag{16}$$

The DRT demand was subsequently visualized on a map. To provide context and comparative insights, corresponding maps were created to visualize the distribution of the female and elderly populations using 2020 Census data.

Then, the DRT accessibility for each Census block was computed by averaging the travel distances of specific DRT trips originating from within the block, as shown in **Equation (17)** and **Equation (18)**. The overall DRT accessibility represented the average travel distance for total DRT trips. The average travel distances for DRT trips made by females and the elderly were also calculated separately. Moreover, to understand the DRT accessibility to access essential destinations, the average trip distance for DRT trips was calculated for three specific trip purposes: home-healthcare (trip with destination land use of healthcare facilities), home-leisure (trip with destination land use of shopping stores and churches), and home-service (trip with destination land use of government offices and banks). This was done using **Equation (17)** for each trip purpose type.

$$Transit\_access_{ij} = \frac{\sum_N trip\ \ distance\ _{ijn}}{N} \tag{17}$$

$$Transit\_access_i = \frac{\sum_j distance\ _{ij}}{J} \tag{18}$$

Where:

N is the number of DRT trips originating from the block i to access the specific trip purpose j;

n is the n_{th} DRT trip;

$Trip\ distance_{ij}$ is the average trip distance from the block i to access the specific trip destination with purpose j;

J is the number of DRT trip purposes;

j is the j_{th}trip purpose; and

$trip\ distance_i$ is the average trip distance of DRT trips with all trip purposes originating from the block i.

This analysis involved the visualization of DRT trip distances, where shorter distances were interpreted as indicative of higher accessibility and longer trip distances were indicative of lower accessibility.

The final part of the spatial analysis aimed to classify the spatial relationship between DRT trip counts (demand) and trip distances (accessibility). Census blocks were classified into four categories (low or high) based on two criteria: the median value of DRT trip count and the median value of DRT trip distance, as illustrated in **Figure 6**. For example, a Census block was classified as “high demand-low accessibility” if it exceeded the median DRT trip count of all blocks, and the average DRT trip distance of this block exceeded the median value of the average trip distances for all blocks. Census blocks categorized as “high demand-low accessibility” were recognized as possible areas of concern, which were then deemed potential essential destination deserts.

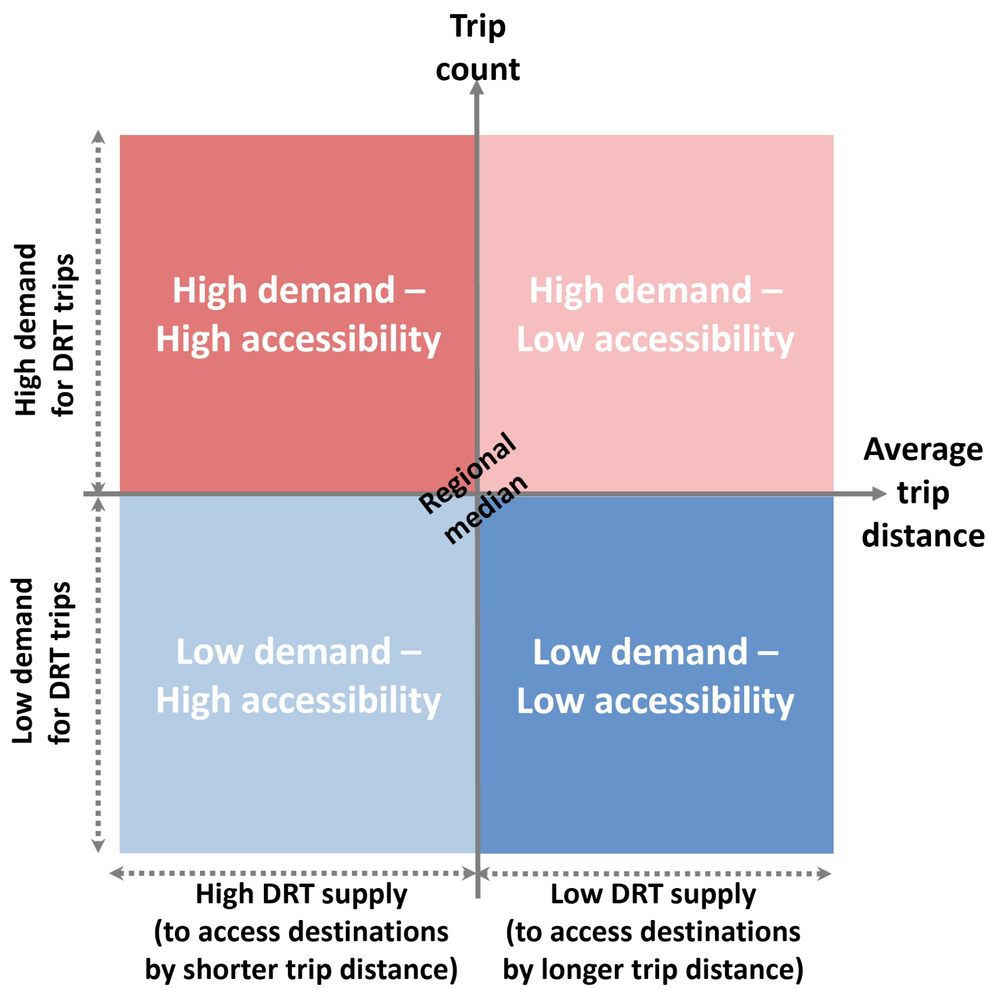


Figure 6 Classification of the number of DRT trips and DRT trip distance

Chapter 4 Results and Discussion

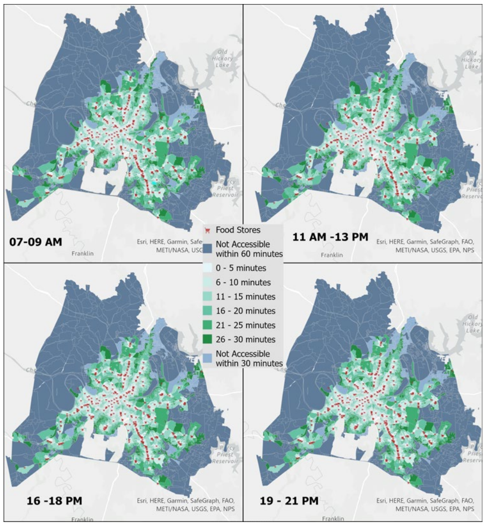
4.1 Results and discussion on FRT accessibility and equity analysis in Nashville, Memphis, Chattanooga, and Knoxville

This section presents the results of the FRT analysis in four parts. The first part maps the distribution of travel time to access the nearest essential service facility (i.e., food store, healthcare facility, childcare facility, school, and park entrance) in the four study areas: Nashville, Memphis, Chattanooga, and Knoxville. The next two parts visualize the transit supply index and transit demand index for each of the study areas. The fourth part assesses the spatial match and mismatch between transit supply to access essential services and potential transit demand and identifies underserved areas as essential service deserts.

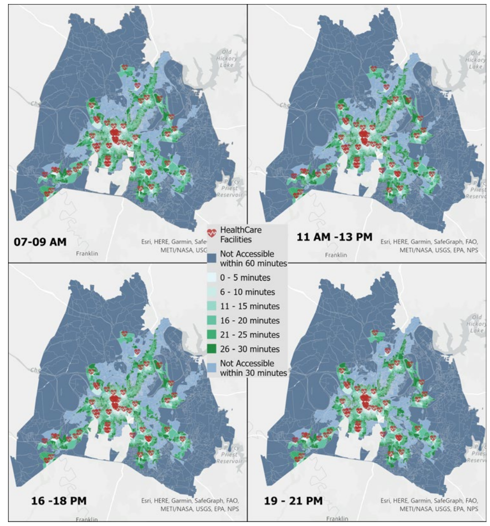
4.1.1 Transit travel time to access the nearest essential service facility

This part applied the method discussed in section 3.3.1 to measure the spatial transit travel time for accessing the nearest five essential service categories. The results are shown separated for each of the four cities. The maps with spatial transit accessibility in Nashville are shown in **Figure 7** below. The results for the other three cities are included in Appendix 3.

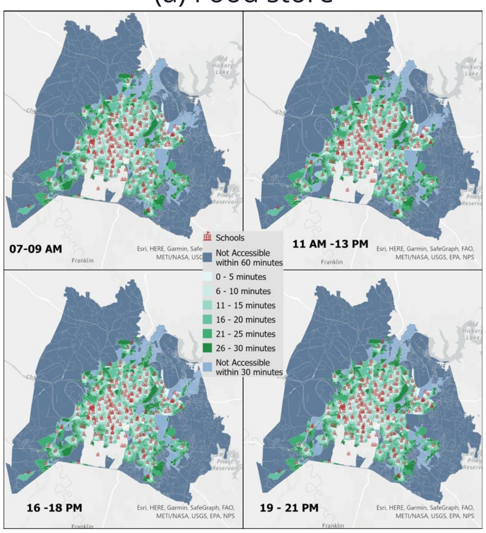
These maps compare transit accessibility to five essential services across four time windows: AM peak (7 am to 9 am), midday (11 am to 1 pm), PM peak (4 pm to 6 pm), and evening (7 pm to 9 pm). In Nashville, parks exhibit a different distribution pattern and are more likely to be located on the outskirts of the city. Additionally, in comparison to food stores, schools, and childcare facilities, healthcare facilities are less evenly distributed across the city and are more densely concentrated around downtown areas. In contrast to Nashville, Memphis has food stores, schools, childcare facilities, and parks more evenly distributed throughout most of the city. However, in Memphis, most areas are unable to access healthcare facilities within 30 minutes, as these facilities are concentrated around specific small areas. Compared to Nashville and Memphis, Chattanooga has fewer essential services, particularly healthcare facilities. Knoxville also has numerous areas with limited transit accessibility to healthcare facilities, but it features relatively evenly distributed transit accessibility to the other four essential services (food stores, schools, childcare, and parks) across most of the city. In terms of changes in transit accessibility to specific services throughout the day in four cities, substantial differences across various time windows were not observed from these visualizations.



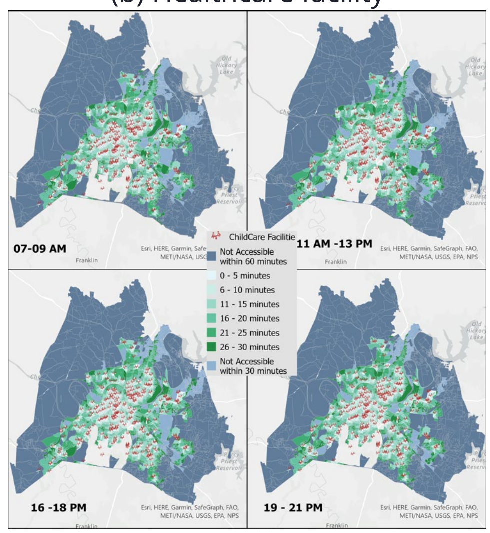
(a) Food store



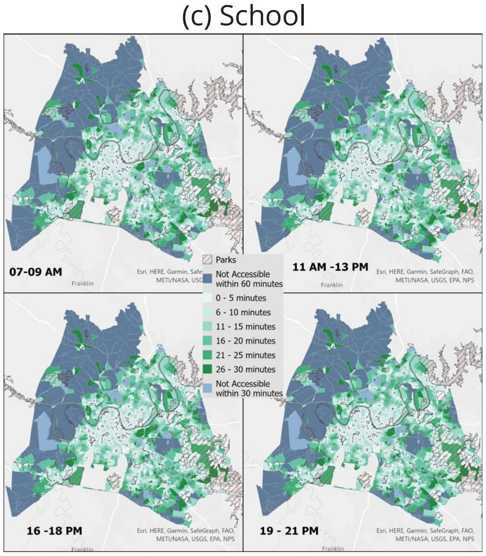
(b) Healthcare facility



(c) School



(d) Childcare facility



(e) Park

Figure 7 Travel time to access the nearest essential service facility in Nashville

4.1.2 Transit supply index

This part applied the method discussed in section 3.3.3 to compute the spatiotemporal transit supply index for the five essential service categories. To enable comparison between maps for a city, **Figure 8 - Figure 11** employed equal interval classifications to visualize the transit supply index at the Census block group level. The map in the bottom right corner displays transit networks (Nashville's WeGo, Memphis MATA, Chattanooga CARTA, and Knoxville KAT), and the remaining maps depict the transit supply index with overlaid essential service facility locations (e.g., one map showing food stores, one showing healthcare facilities, etc.). These transit supply index maps utilized a consistent reference scale and legend, with darker shades of blue representing higher levels of transit supply to access essential services. The following results are shown for each of the four cities.

1) Nashville

The maps in **Figure 8** reveal several noteworthy spatial patterns of transit supply level in Nashville. First, the downtown area of Nashville has the highest transit supply levels regardless of the essential service category. Second, areas with denser transit stops and more essential service facility locations generally correspond to higher transit supply levels (as would be expected). Third, there is a consistent trend of decreasing transit access to food, healthcare, school, and childcare as one moves away from the city center and towards the outskirts of Nashville. Finally, the distribution of transit supply to access parks is somewhat different, with higher transit supply levels concentrated in the central and south/east areas of Nashville. This is likely because recreational amenities and green spaces, particularly larger parks, are often located in suburban areas of the city. Based on these findings, it can be noted that certain areas in Nashville encounter limited access to one or several types of essential services via transit.

2) Memphis

The maps in **Figure 9** show the spatial distribution of transit supply levels in Memphis. As would be expected, areas with denser transit stops and more essential service facility locations generally correspond to higher transit supply levels. However, in comparison to the distribution of transit supply in Nashville, transit supply for accessing healthcare and parks differs in Memphis. Particularly, the transit supply for accessing healthcare stands out as being distributed differently from the transit supply for accessing the other four essential services. This distinction arises because healthcare facilities in Memphis are centrally located in specific areas, unlike the more evenly distributed locations of the other four services. Furthermore, Memphis exhibits a more even distribution of recreational facilities and green spaces throughout the city compared to Nashville.

3) Chattanooga

The map in **Figure 10** shows the spatial distribution of transit supply levels in Chattanooga. Compared to Memphis, the transit service areas in Chattanooga are much smaller. This, combined with fewer service facilities, results in a limited transit supply for accessing essential services, particularly for healthcare accessibility, as most areas have a restricted level of transit supply for accessing healthcare services. Last, it should be noted that the maps of Chattanooga do not include the nearby area of Red Bank.

4) Knoxville

The map in **Figure 11** shows the spatial distribution of transit supply levels in Knoxville. For Knoxville, a similar spatial distribution pattern was observed for transit supply levels across all five essential services. Additionally, a limited transit supply level was observed in southeast Knoxville, where there is limited FRT network coverage.

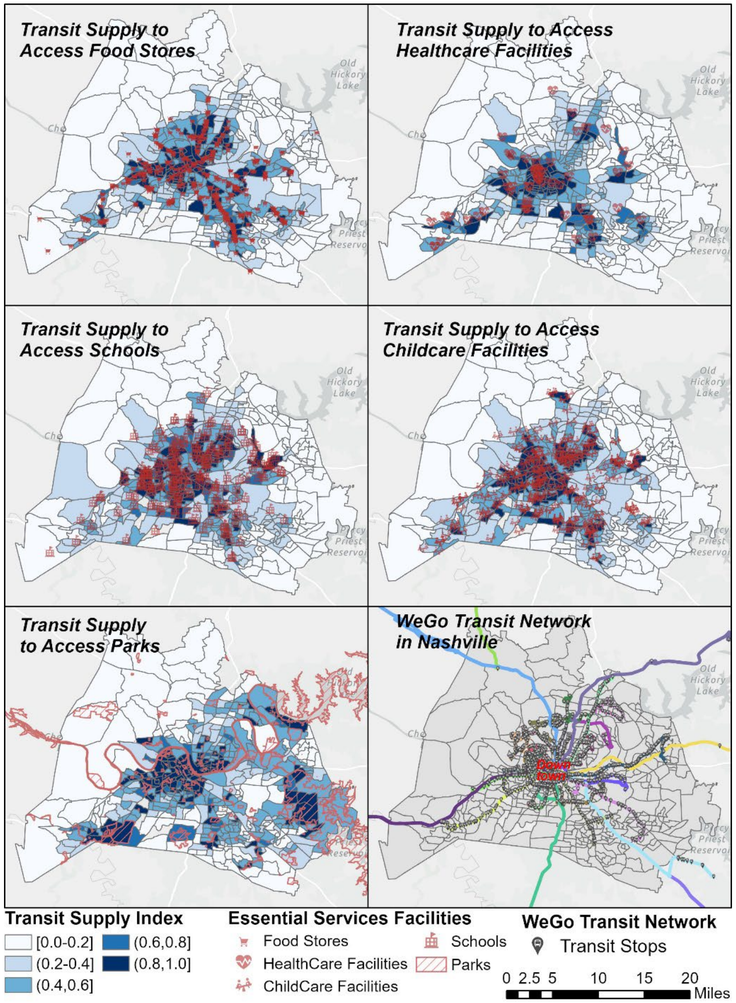


Figure 8 Distribution of the transit supply index to the five essential service categories in Nashville

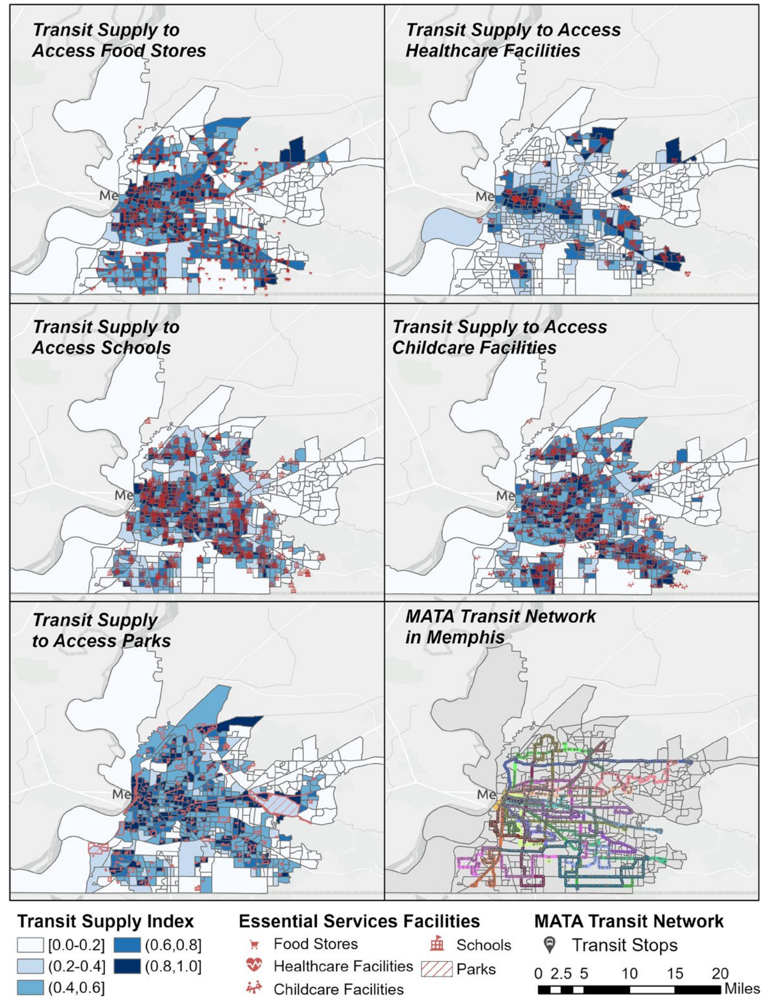


Figure 9 Distribution of the transit supply index to the five essential service categories in Memphis

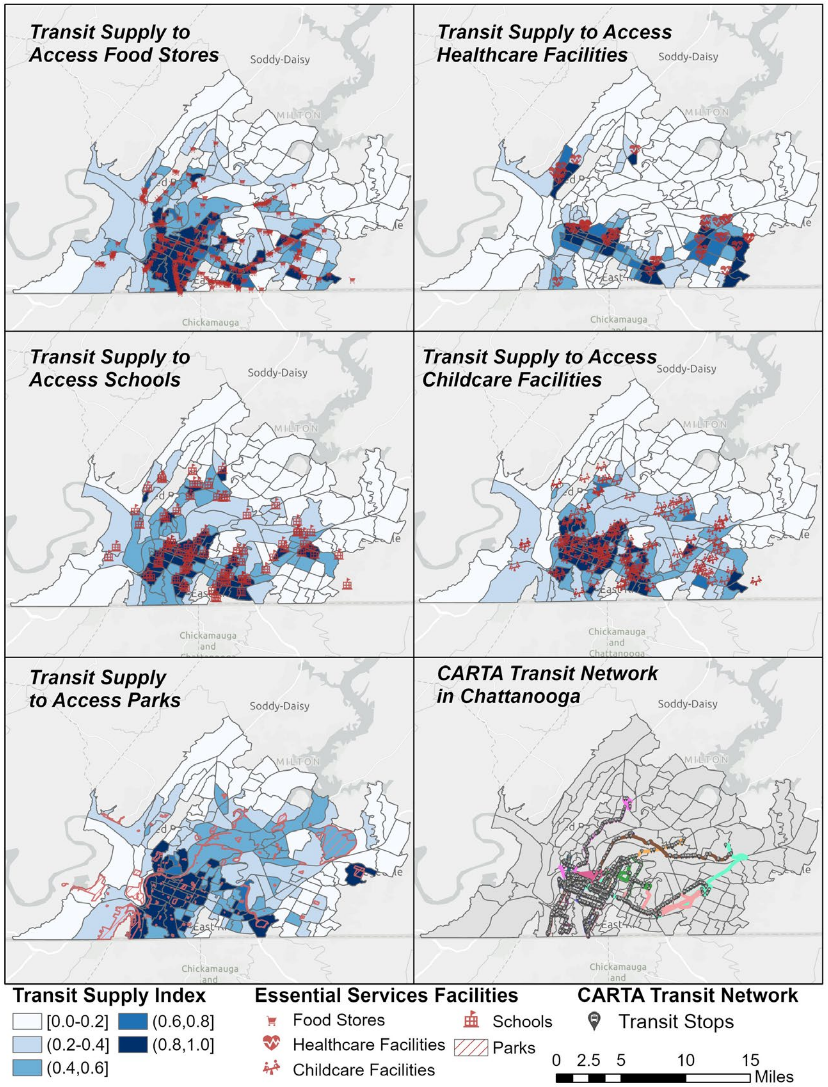


Figure 10 Distribution of the transit supply index to the five essential service categories in Chattanooga

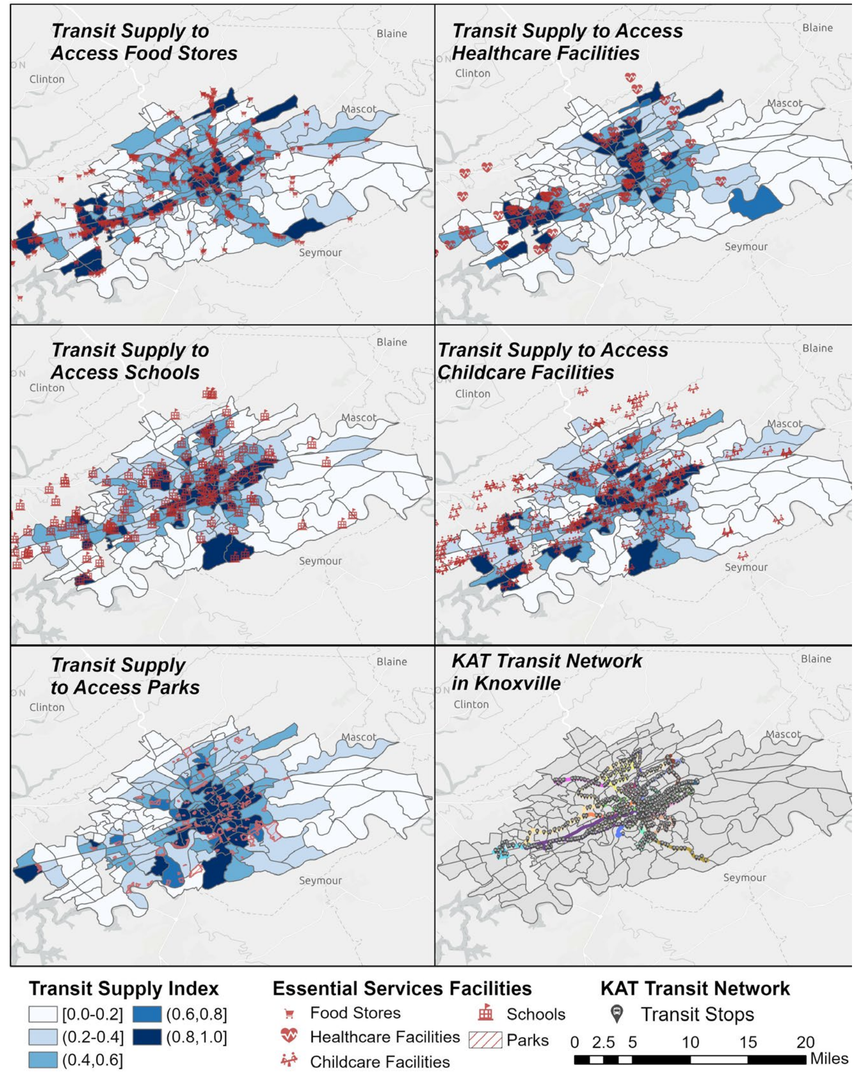


Figure 11 Distribution of the transit supply index to the five essential service categories in Knoxville

4.1.3 Transit demand index

This part applied the method discussed in section 3.3.4 to compute the transit demand index for three groups (car-limited, poverty, minority) in the four cities. **Figure 12** displays the distribution of the transit demand index at the Census block group level in Nashville, utilizing the equal interval classification method. The transit demand index maps for the other three cities were included in Appendix 4. The color scheme was created based on the value of the normalized transit demand population, with darker shades of orange-brown indicating higher levels of potential transit demand.

As can be seen in **Figure 12**, most areas in Nashville exhibit relatively low levels of potential transit demand, as indicated by the lightest orange color. This finding aligns with the sociodemographic characteristics of Nashville, where approximately 15% of residents fall below the poverty line, 38% of residents are minorities (non-white), 14% of residents identify as Hispanic or Latino, and only 6% of households do not own vehicles. Despite variations in the distribution of different transit groups, there are some areas of overlap among them. For instance, one block group located in southeast Nashville has the highest transit demand index level for all three groups, indicated by the darkest orange shade.

In Memphis, an increased transit demand was noted, with particularly high demand observed from the minority population in both the northern and southern areas. Chattanooga, on the other hand, exhibits a comparable distribution of transit demand among car-limited, poverty, and minority populations, suggesting a potential overlap among these three groups. In Knoxville, lower demand was observed from those in poverty.

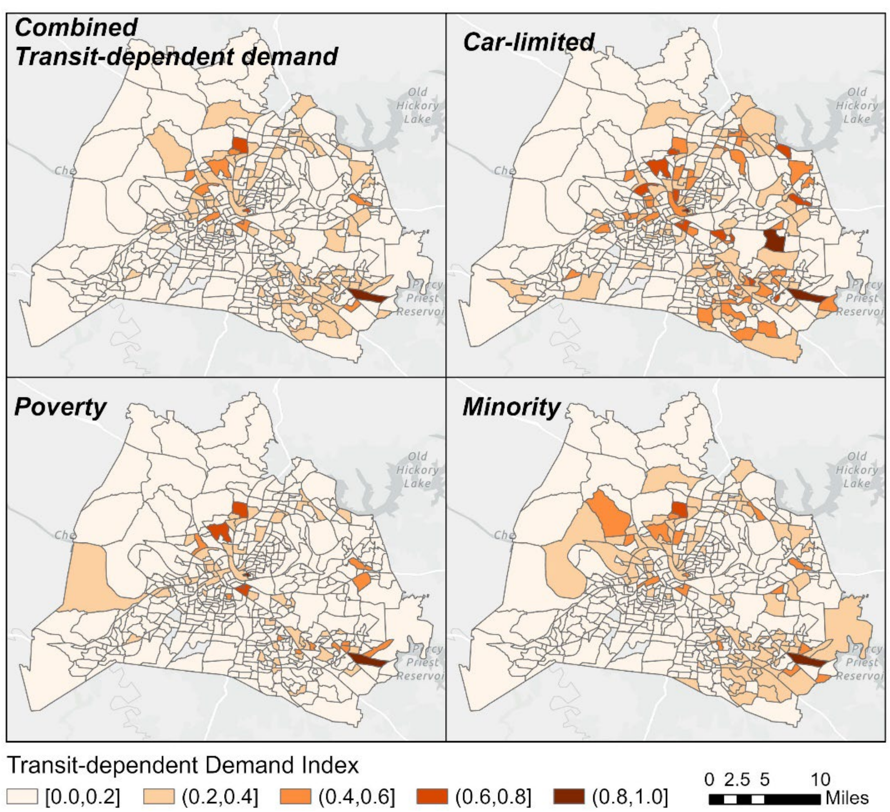


Figure 12 Distribution of the transit demand index in Nashville

4.1.4 LISA clustering and identification of essential service deserts

The bi-LISA maps in **Figure 13, Figure 14, Figure 15, and Figure 16** visualize the spatial match and mismatch between transit demand and transit supply to access essential services by categorizing block groups into four types of significant spatial correlation clusters. It is noted that a 5% significance level was used to determine the statistical significance of the calculation of local Moran's *I*, with block groups having a p-value above this threshold classified as not significant. The matched correlation consists of H-H clusters (shown in red), indicating high potential transit demand and high supply areas, and L-L clusters (indicated in indigo), representing areas with low potential transit demand and low transit supply to access essential services. The mismatched pattern includes two types, namely the H-L clusters (indicated as pink), which highlight underserved areas with high levels of potential transit demand but limited access to essential services via transit, and the L-H clusters (indicated as light blue), indicating areas with low potential transit demand but high transit accessibility, which are considered overserved areas. The summary of the four bi-LISA clusters was visualized in bar plots that are included in Appendix 5: Bi-LISA bar charts in Nashville, Memphis, Chattanooga, and Knoxville.

In general, the majority of H-H clusters (high demand and high supply) and L-H clusters (low demand and high supply) are concentrated in the central city area characterized by a high density of transit stops and numerous essential service facilities. In contrast, most H-L clusters (high demand and low supply) and L-L clusters (low demand and low supply) are distributed on the peripheries of the city. The following results are briefly discussed for each of the four cities.

1) Nashville

In Nashville, different distribution patterns can be observed between clusters of transit supply to access parks and clusters of transit supply to access the other four essential services. As an illustration, in terms of combined demand groups (shown in the first column n **Figure 13**), it is noted that the number of H-L clusters is higher for food stores, healthcare, schools, and childcare facilities compared to parks. This indicates that communities with high potential transit demand have less access to food stores, healthcare facilities, schools, and childcare facilities than to parks. Furthermore, within the southeastern region of the city, H-L clusters can be observed for food stores, healthcare, schools, and childcare facilities, whereas there are few H-L clusters.

The cross-sectional comparison reveals spatial disparities in transit supply to access essential services for different demand groups. Specifically, in terms of transit accessibility to food stores, healthcare facilities, schools, and childcare facilities (represented in the first four rows in **Figure 13**), H-L clusters (pink areas) were identified on the southeast edge and in the mid-northwest areas for minority groups, while these areas were classified as L-L clusters (blue areas) for car-limited groups and poverty groups. These findings imply that the southeast and mid-northwest areas of Nashville, with limited transit access, have a higher potential transit demand from minority populations. The H-L clusters for food store access, school access, and park access were observed for the poverty group in the southwest corner of the city, whereas the same communities were classified as L-L clusters for car-limited groups and minority groups. This implies that the underserved regions in the southwest corner of the city exhibit a greater demand from the poverty group.

By examining the count of block groups in each cluster shown in **Figure 49,** it becomes apparent that there is a larger proportion of H-L clusters (indicated by the pink bar) in the food store, healthcare, school, and childcare categories than in the park category. Moreover, the healthcare, school, and childcare categories have a greater number of H-L clusters than the food store category. This implies that there are greater levels of transit inequity regarding access to healthcare facilities, schools, and childcare facilities, as opposed to food access and park access. In terms of potential transit demand, a greater proportion of H-L clusters was observed within minority groups, indicating that compared to those who are car-limited and in poverty, minority groups encounter more pronounced transit inequity.

2) Memphis

In general, the High-Low (H-L) clusters for food stores, healthcare, schools, and childcare were predominantly distributed around the north, east, and south edges of Memphis (see **Figure 14)**. However, H-L clusters for parks were only observed in the east and southeast edges of Memphis. When conducting a cross-sectional comparison, there is only a slight difference in transit supply to access specific essential services for different demand groups. This might result from the fact that transit demand in the three population groups exhibits a similar spatial distribution.

Examining the bar chart of bi-LISA clusters presented in **Figure 50** reveals a notable concentration of essential deserts within minority population groups. Across the spectrum of five essential services, healthcare deserts emerge as particularly prevalent, demonstrating a higher incidence within each demand group.

3) Chattanooga

Figure 15 displays the Bi-LISA cluster maps depicting various combinations of transit supply categories and transit demand groups in Chattanooga. Most High-Low (H-L) clusters are notably concentrated in the north edge of Chattanooga. However, distinct spatial distribution patterns can be observed among clusters representing transit supply for different essential services. For instance, a Census block near the central area of Chattanooga is classified as an H-L cluster (identified as a pink area) specifically for food stores, healthcare, and schools. This block is situated close to the transit network, as indicated by the transit network distribution map in **Figure 10**. The limited accessibility in this area may result from an insufficient number of facilities for food stores, healthcare, and schools.

4) Knoxville

Figure 16 illustrates the Bi-LISA cluster maps for Knoxville. Generally, Knoxville demonstrates a distinctive pattern with fewer occurrences of High-Low (H-L) clusters (pink areas) in comparison to the other three cities. However, Knoxville also features some H-L clusters positioned closer to the city center. In the context of combined transit demand, the majority of H-L clusters are concentrated in northwest Knoxville, indicating specific transit challenges in this region. However, further analysis considering demand groups individually reveals some different patterns. Areas characterized by low transit accessibility to essential services and high demand from car-limited populations are dispersed across the north, mid-west, and mid-south regions of Knoxville. Besides those areas near the city center, there is also a high demand from people facing poverty and belonging to minority groups in the eastern parts of Knoxville, where transit access to all essential services is limited. These spatial patterns underscore the complexity of essential service desert dynamics in Knoxville, emphasizing the need for a detailed approach to address the specific difficulties experienced by diverse segments of the population in different parts of the city.

However, the positive aspect is that, in terms of the count of essential service deserts, Knoxville has the least number of deserts compared to other cities. Moreover, the majority of these deserts are related to healthcare and parks, as depicted in **Figure 52**.

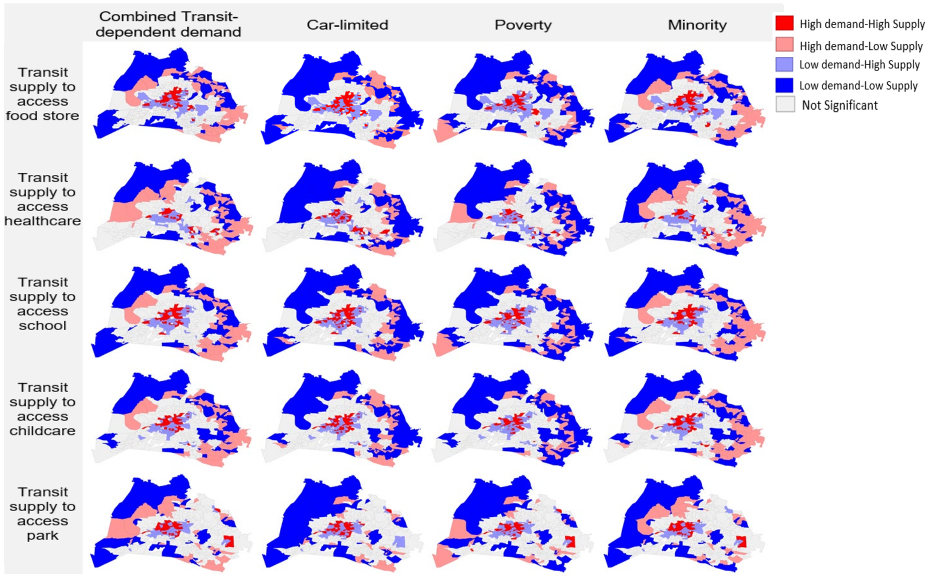


Figure 13 Bi-LISA cluster maps for different combinations of transit supply categories and transit demand groups in Nashville

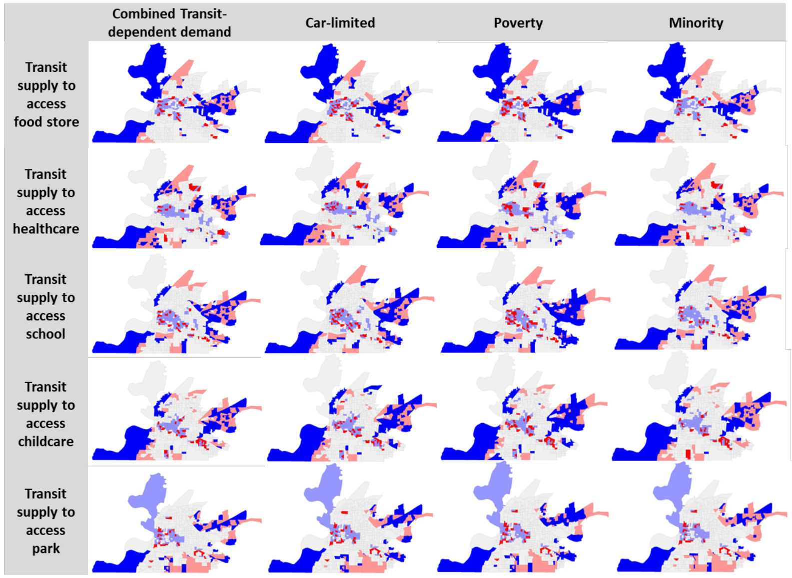


Figure 14 Bi-LISA cluster maps for different combinations of transit supply categories and transit demand groups in Memphis

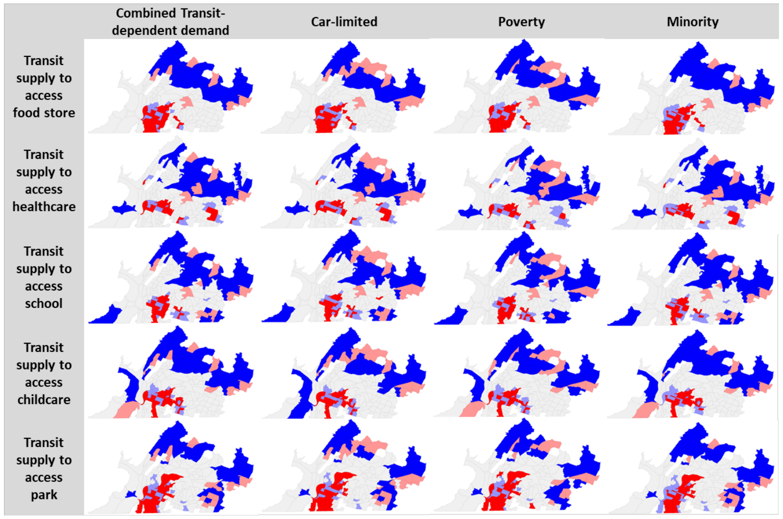


Figure 15 Bi-LISA cluster maps for different combinations of transit supply categories and transit demand groups in Chattanooga

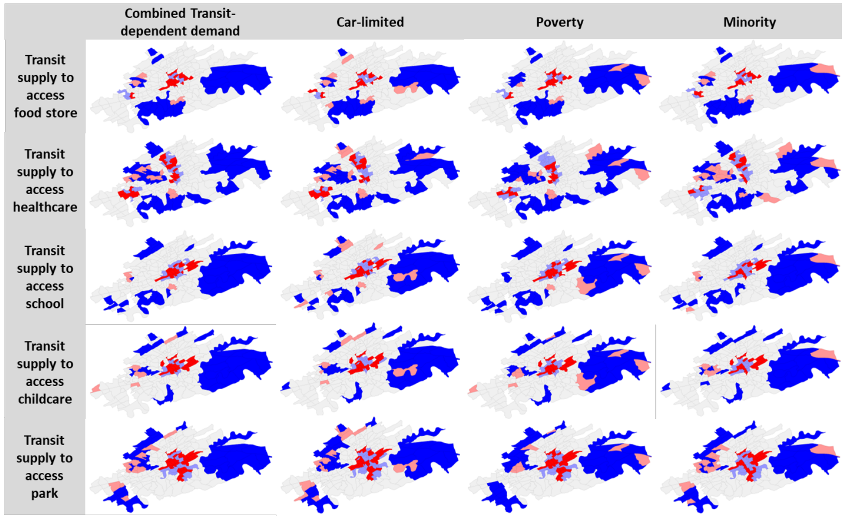


Figure 16 Bi-LISA cluster maps for different combinations of transit supply categories and transit demand groups in Knoxville

4.2 Transit improvements in areas with limited access

This section considers potential transit system modifications at locations with limited transit access to essential services. The method is demonstrated for a single case study (location) in each of the four cities, beginning with Nashville.

4.2.1 Case study in Nashville

Before proposing potential transit modifications, areas with multiple essential services were visualized by overlapping the LISA clustering maps shown in the previous section. In Nashville, the co-location map of food deserts, healthcare deserts, school deserts, childcare deserts, and park deserts to the combined transit demand group is shown in **Figure 17**. It shows nine block groups (the shaded pink communities) were found to be transit deserts with respect to all five essential services, distributed across the mid-northwest, northeast edge, and southeastern edge of Nashville.

Next, a comprehensive examination of the transit services and network distribution in each area encompassing all five essential service deserts was conducted. As depicted in **Figure 18**, the two Census block groups highlighted in teal were pinpointed as transit deserts in relation to all five essential services. The investigation of the surrounding transit network and facility distribution indicated proximity to transit networks, with some service facilities observed in the vicinity of these areas. These two areas were chosen as case studies in Nashville. Subsequently, a hypothetical transit modification for this specific case study was then assessed.

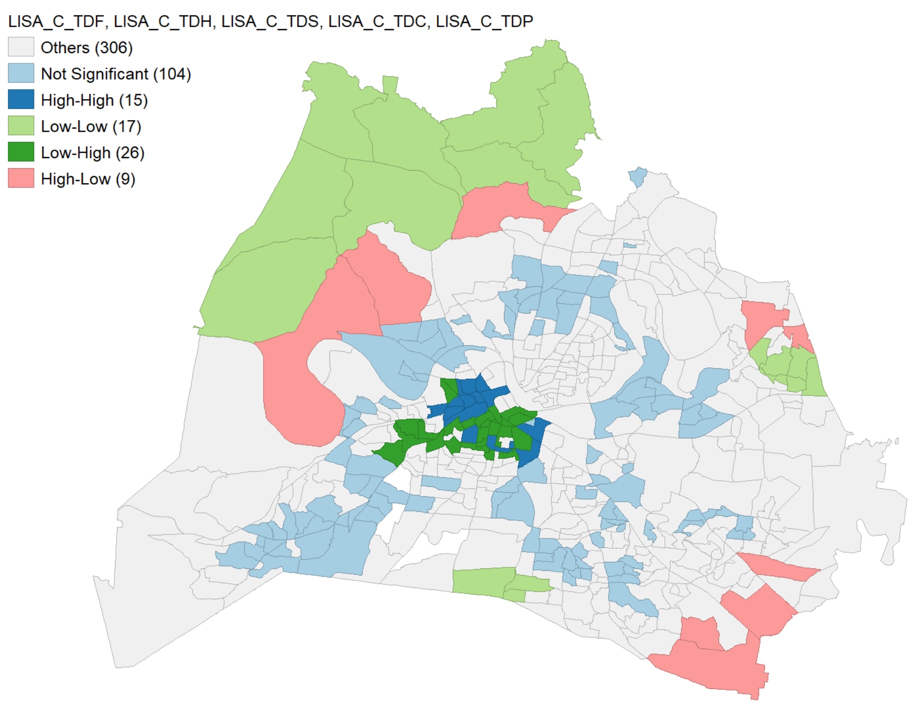


Figure 17 Co-location maps of food deserts, healthcare deserts, school deserts, childcare deserts, and park deserts in Nashville

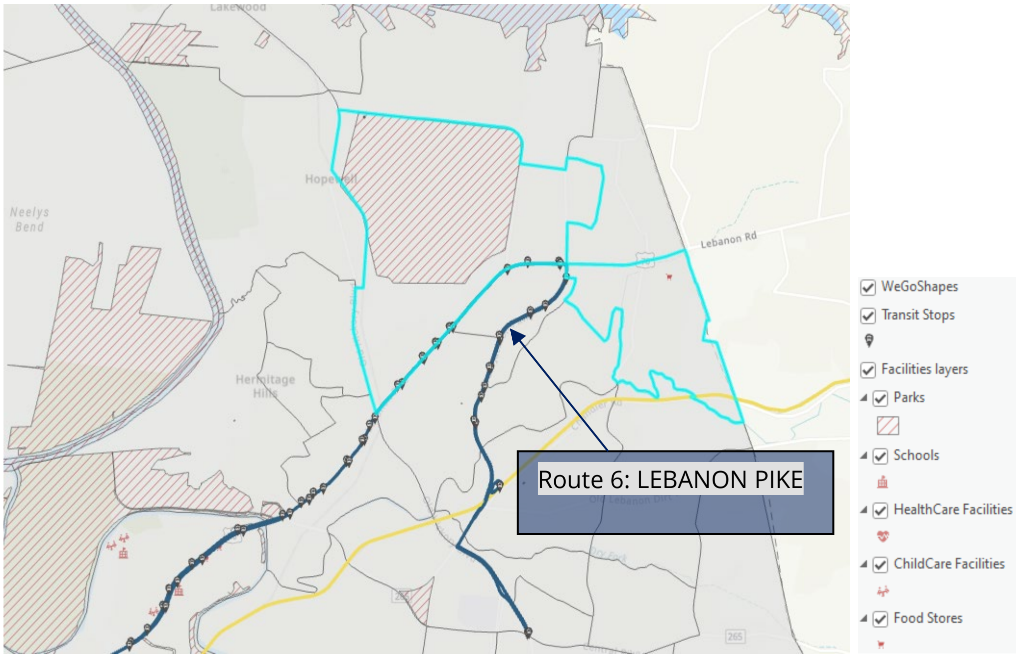


Figure 18 Screenshot of surrounding transit network and essential service facilities distribution around overlapping essential service deserts in the mid-northwest of Nashville

Transit information in Nashville was obtained from February 2023 GTFS provided by WeGo Public Transit. Route 6: Lebanon Pike is the closest transit route to the study area. Route 6 offers transit services between downtown and the study area, operating from 5 am to 11 pm. During the AM peak on weekdays, the headway is approximately 45 to 60 minutes, indicating good temporal transit service coverage. Therefore, a spatial modification to Route 6 could be considered as an added trip pattern.

To illustrate the before and after evaluation, the origin point was put in a large residential complex as shown in blue icon in **Figure 19**. The spatial distribution of the proposed added trip pattern is depicted by the blue line in **Figure 19**, which originates from the existing Route 6 and concludes at the endpoint of Route 6. **Figure 20** shows the assessment of the changes of transit accessibility to the nearest food store within the essential service desert areas studied, both before and after the hypothetical incorporation of trip patterns as a supplement to the existing Route 6. The result suggests that, after modification, the residents in the study area could potentially access the nearest food store in 26 minutes (as opposed to 43 minutes before modification).

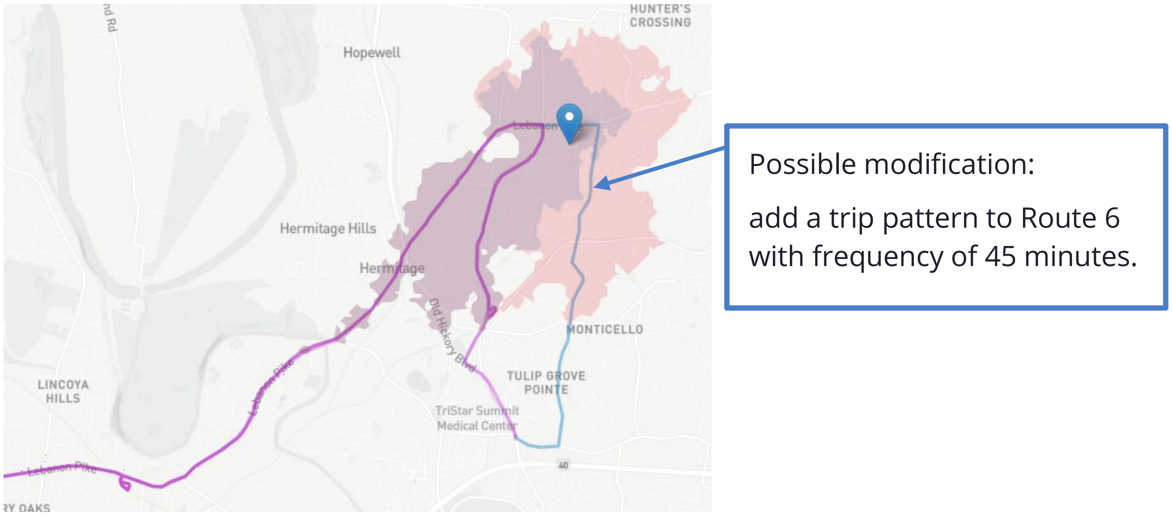


Figure 19 Overlapping isochrones before and after hypothetical modification to WeGo Route 6

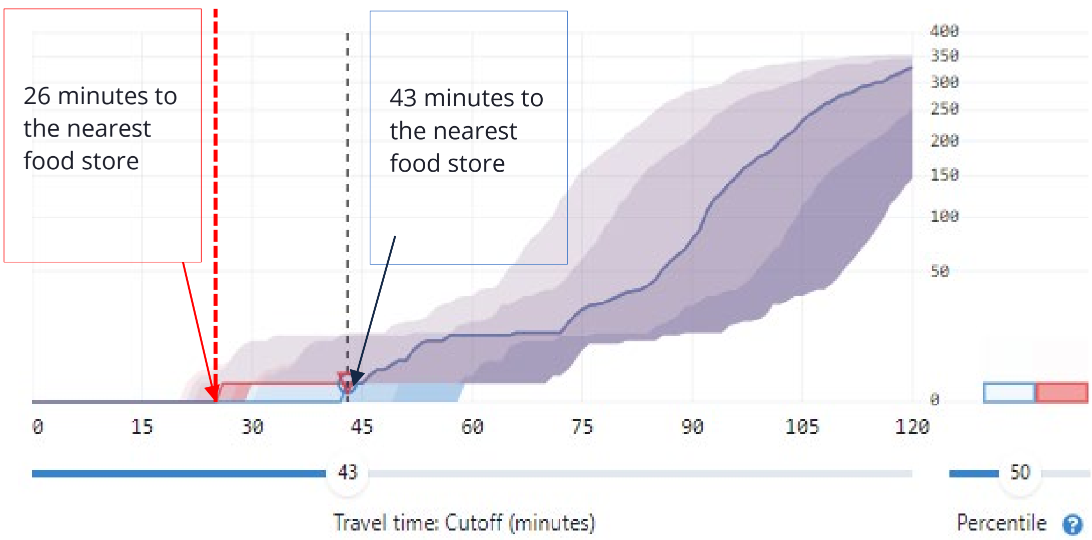


Figure 20 Transit accessibility results before and after hypothetical modification to WeGo Route 6

4.2.2 Case study in Memphis

The co-location map of food deserts, healthcare deserts, school deserts, childcare deserts, and park deserts for the combined transit demand in Memphis is shown in **Figure 21.** It shows eight block groups (the shaded pink communities) were found to be transit deserts with respect to all five essential services, distributed near the eastern edge of Memphis. The area within the red circle is the case study in Memphis.

As shown in **Figure 22**, Route 19 was the closest transit route to the case study. Route 19 provides transit service between Downtown and Vollintine during 5 a.m. to 7 p.m., and the headway was 120 minutes during the AM peak on weekdays. The map shown in **Figure 22** indicates relatively good spatial access from the study area to transit. Therefore, the hypothetical transit modification proposed for this case study is to modify the headway of Route 19 from 2 hours to 1 hour.

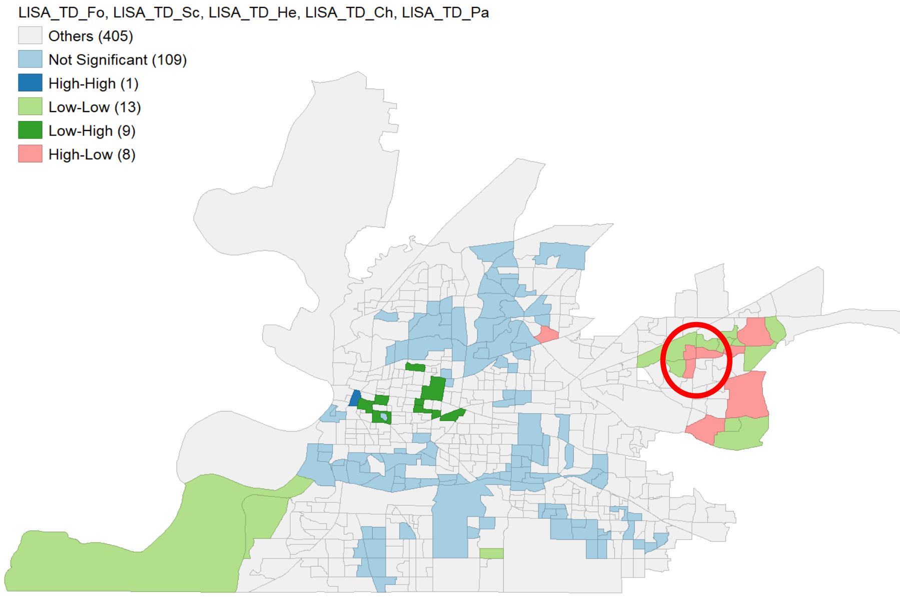


Figure 21 Co-location maps of food deserts, healthcare deserts, school deserts, childcare deserts, and park deserts in Memphis

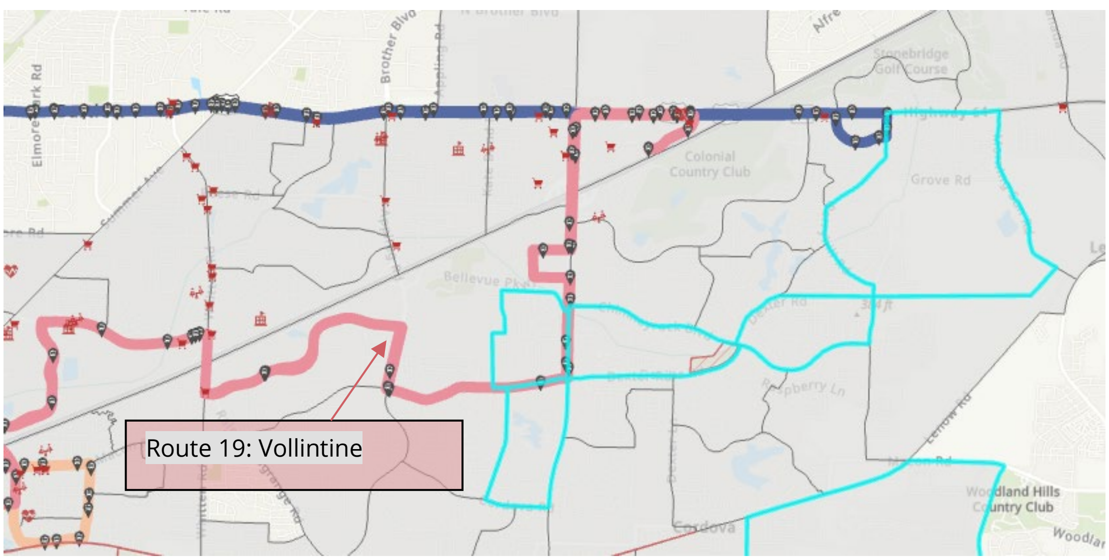


Figure 22 Screenshot of surrounding transit network and essential service facilities distribution around overlapping essential service deserts in eastern Memphis

Figure 23 and **Figure 24** show the hypothetical assessment of the changes of transit accessibility to the nearest food store within the essential service desert areas studied, both before and after converting the frequency of existing Route 19 from 120 minutes to 60 minutes. The result suggests that, after the hypothetical modification, the residents in the study area could access the nearest food store in 47 minutes (as opposed to 65 minutes before modification).

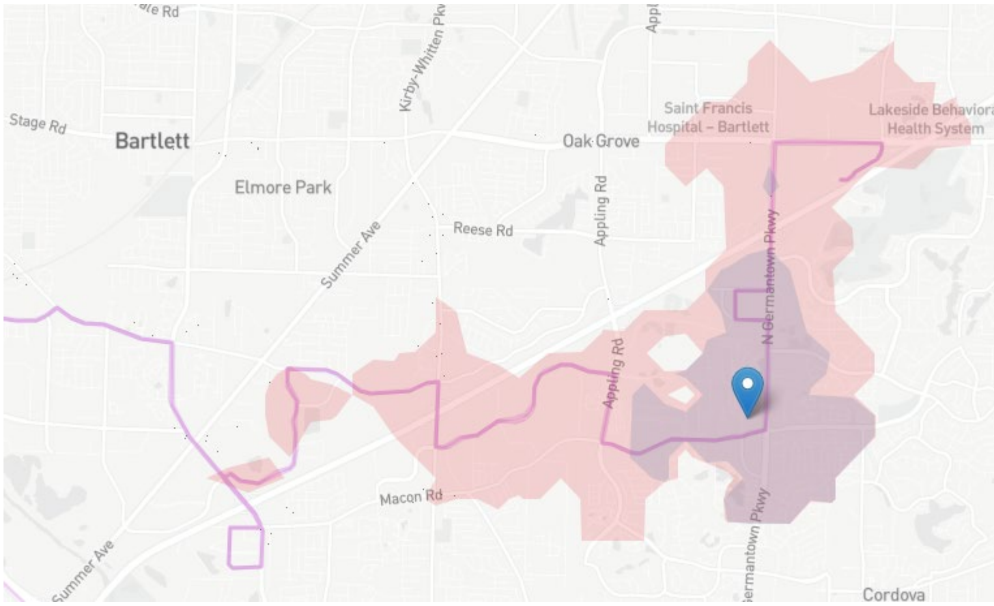


Figure 23 Overlapping isochrones before and after hypothetical modification to MATA Route 19

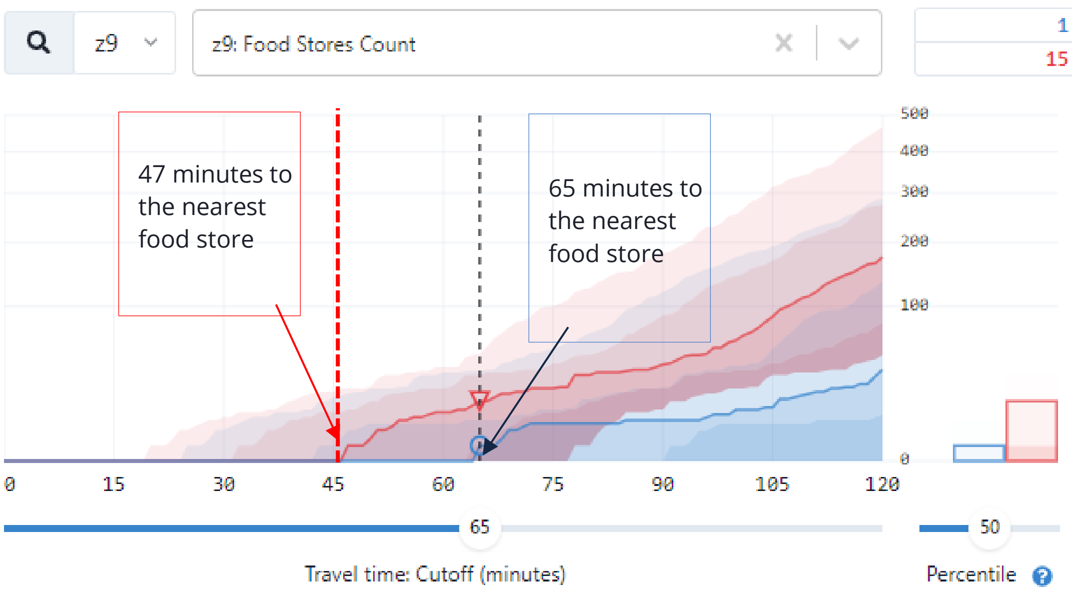


Figure 24 Transit accessibility results before and after hypothetical modification to MATA Route 19

4.2.3 Case study in Chattanooga

The case study in Chattanooga is an area with three overlapping types of essential service deserts, as indicated by the red circle in Figure **25**, which illustrates the co-location maps of food stores, schools, and healthcare facility deserts in Chattanooga. The choice of this case study (within the red circle) was driven by the fact that other essential service deserts were situated at a long distance from the existing transit network. This geographical separation posed a challenge in formulating transit improvements for those cases.

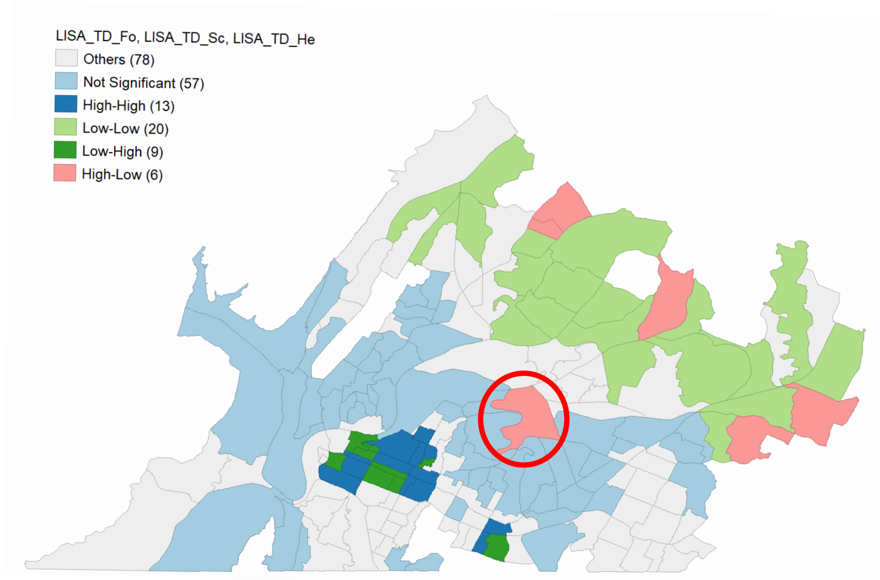


Figure 25 Co-location maps of food deserts, healthcare deserts and school deserts in Chattanooga

As shown in **Figure 26**, Route 10C was the closest transit route to the case study. Route 10C provides transit service between Downtown and East Chattanooga-Campbell St. during 5 a.m. to 8 p.m., and the headway was 45 minutes during the AM peak on weekdays. The map shown in **Figure 26** indicates relatively good spatial access from the study care to transit. Therefore, the hypothetical transit modification proposed for this case study is to modify the headway of Route 10C from 45 minutes to 30 minutes.

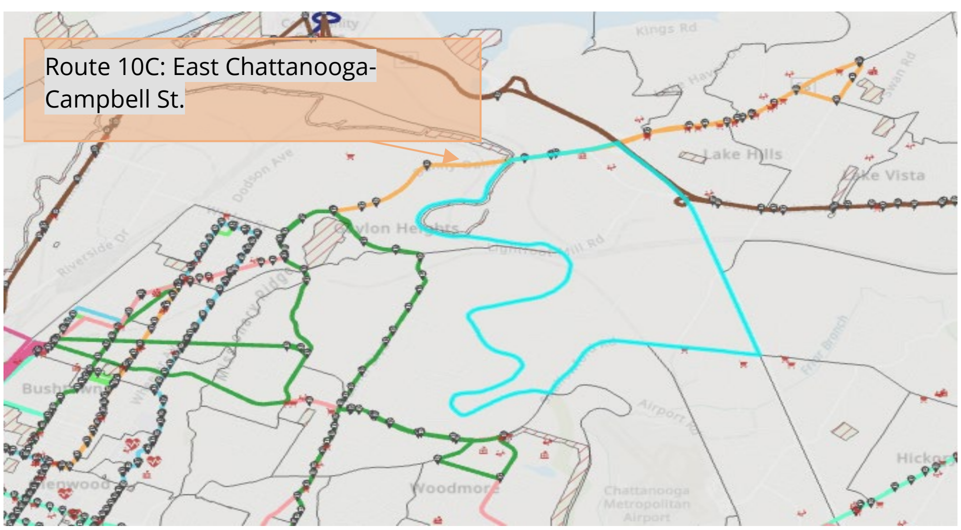


Figure 26 Screenshot of surrounding transit network and essential service facilities distribution around overlapping essential service deserts in case study area of Chattanooga

Figure 27 and **Figure 28** show the hypothetical assessment of the changes of transit accessibility to the nearest food store within the essential service desert areas studied, both before and after converting the frequency of existing Route 10C from 45 minutes to 30 minutes. The result suggests that, after modification, the residents in the study area can access the nearest food store in 32 minutes (as opposed to 72 minutes before modification).

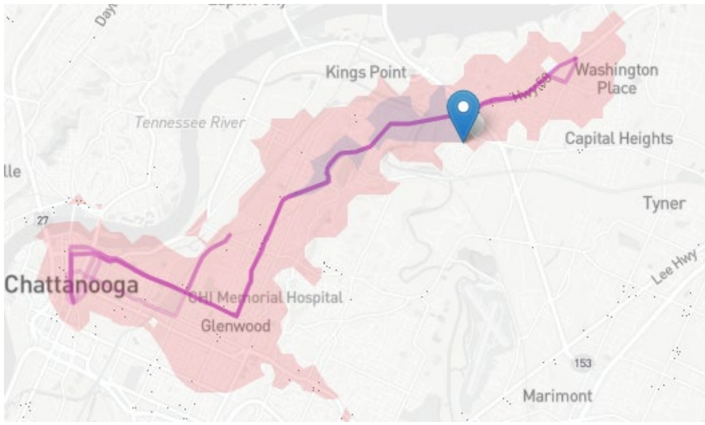


Figure 27 Overlapping isochrones before and after hypothetical modification to CARTA Route 10C

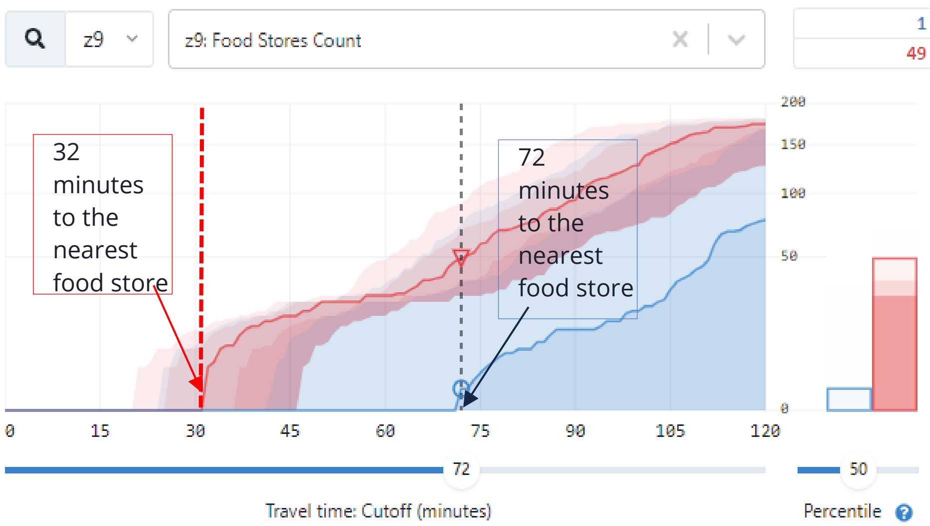


Figure 28 Transit accessibility results before and after hypothetical modification to CARTA Route 10C

4.2.4 Case study in Knoxville

In Knoxville, there are no areas with all five essential service deserts. Consequently, a co-location map (**Figure 29**) depicting the overlap between food and healthcare deserts was used for the case study.

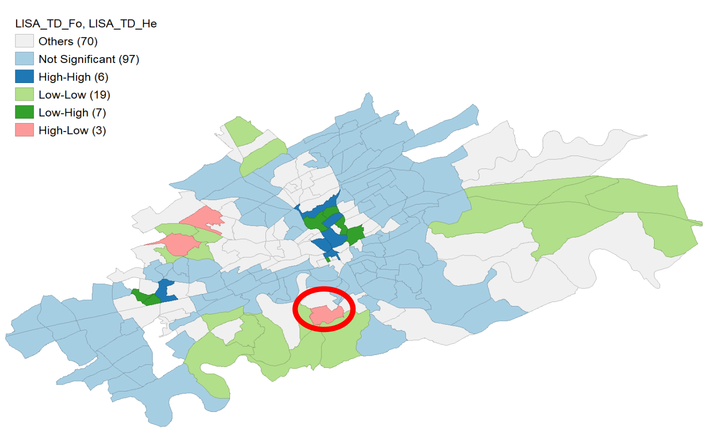


Figure 29 Co-location maps of food deserts and healthcare deserts in Knoxville

As shown in **Figure 30**, Route 45 is the closest transit route to the case study. Route 45 provides transit service between Downtown and Vestal from 5 a.m. to 9 p.m., and the headway was 60 minutes during the AM peak on weekdays. The map shown in **Figure 30** indicates a relatively good spatial access from the study area to the transit network. Therefore, the hypothetical transit modification proposed for this case study is to modify the headway of Route 45 from 60 minutes to 30 minutes.

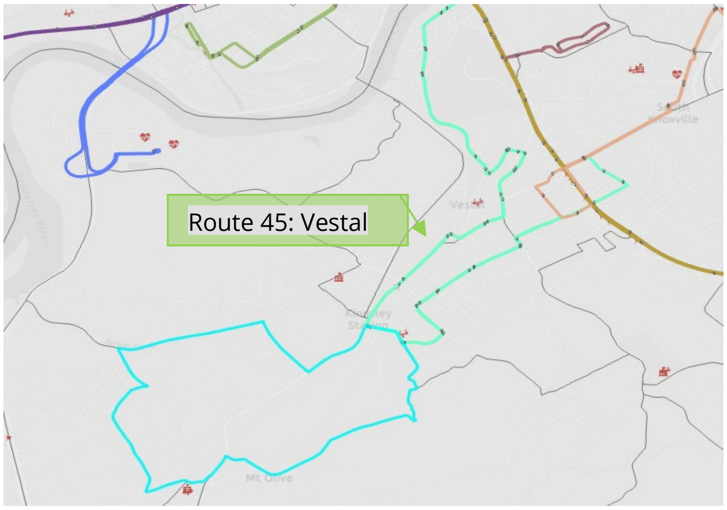


Figure 30 Screenshot of surrounding transit network and essential service facilities distribution around overlapping essential service deserts in case study area of Knoxville

Figure 31 and Figure 32 show the hypothetical assessment of the changes of transit accessibility to the nearest healthcare facility within the essential service desert areas studied, both before and after converting the frequency of existing Route 45 from 60 minutes to 30 minutes. The result suggests that, after potential modification, the residents in the study area could access the nearest healthcare facility in 47 minutes (as opposed to 63 minutes before modification).

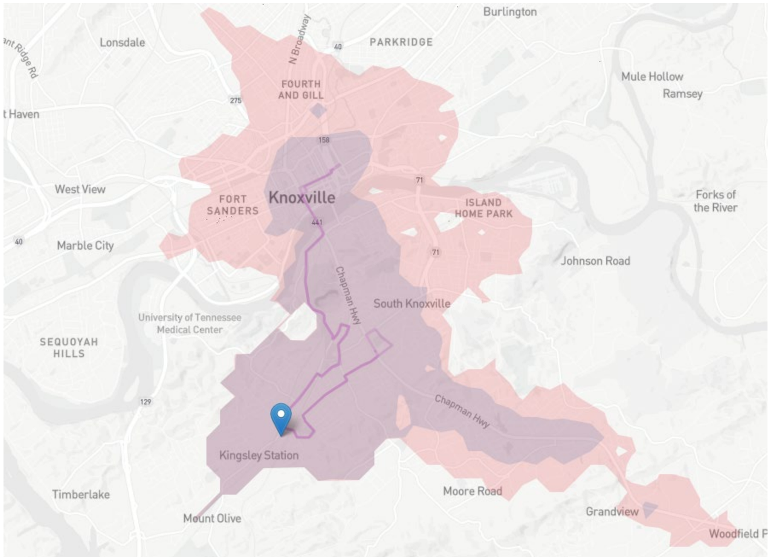


Figure 31 Overlapping isochrones before and after hypothetical modification to KAT Route 45

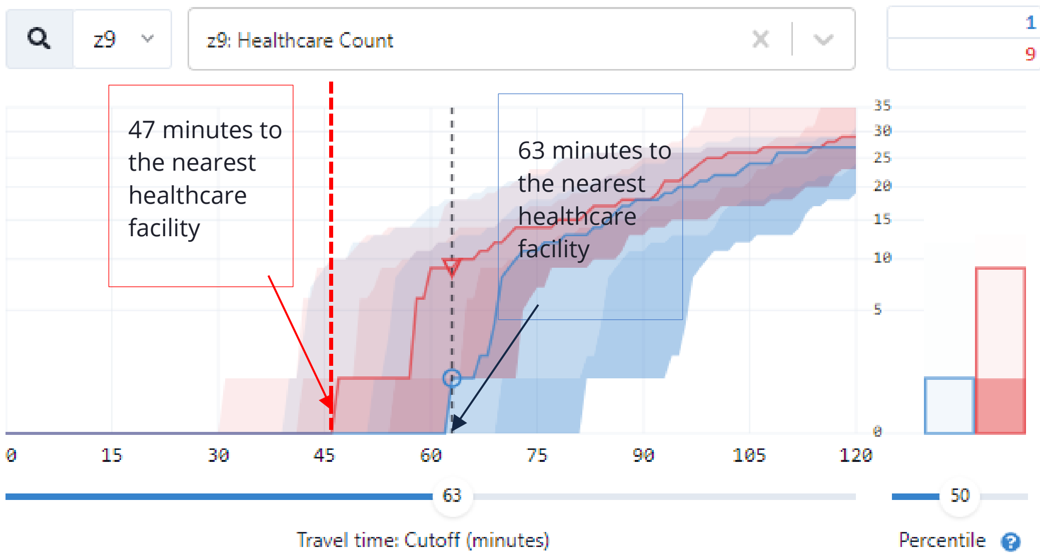


Figure 32 Transit accessibility results before and after hypothetical modification to KAT Route 45

4.3 Results and discussion on DRT accessibility and equity analysis in Morristown

The following sections present the results of the spatial analysis of DRT demand, the spatial distribution of DRT accessibility, and the classification of the spatial relationship between DRT demand and DRT accessibility to identify potential essential destination deserts.

4.3.1 Spatial distribution of DRT demand

This section analyzed the spatial distribution of total DRT demand and DRT demand specifically from two demographic groups: female and elderly. **Figure 33** shows the spatial patterns of total DRT trips, DRT trips taken by the elderly, and DRT trips by females. The orange shading indicates the count of DRT trips; lighter shades represent lower DRT demand levels and darker shades signify higher DRT demand levels. Black circles indicate areas with higher levels of demand from females or the elderly. Blue circles represent areas with a high DRT demand from those who are both female and elderly, green circles depict areas with a higher concentration of DRT trips made by male elderly riders, and red circles show areas characterized by a high density of DRT trips by non-elderly females.

To provide context and comparative insights, corresponding maps of the distribution of the total populations, female populations, and elderly populations from 2020 Census data are presented in **Figure 34**. Notably, these maps revealed that areas with higher population density did not consistently correspond to higher DRT demand. Similarly, areas with higher population density among females and the elderly did not consistently have a higher DRT demand within these demographic groups. For instance, yellow circles in **Figure 34** have a high density of population distribution; however, these Census blocks in **Figure 33** were not shown as high DRT demand. This underscores the limitations of relying solely on Census data for transportation planning, as it may not always accurately reflect actual demand for some modes of travel such as DRT.

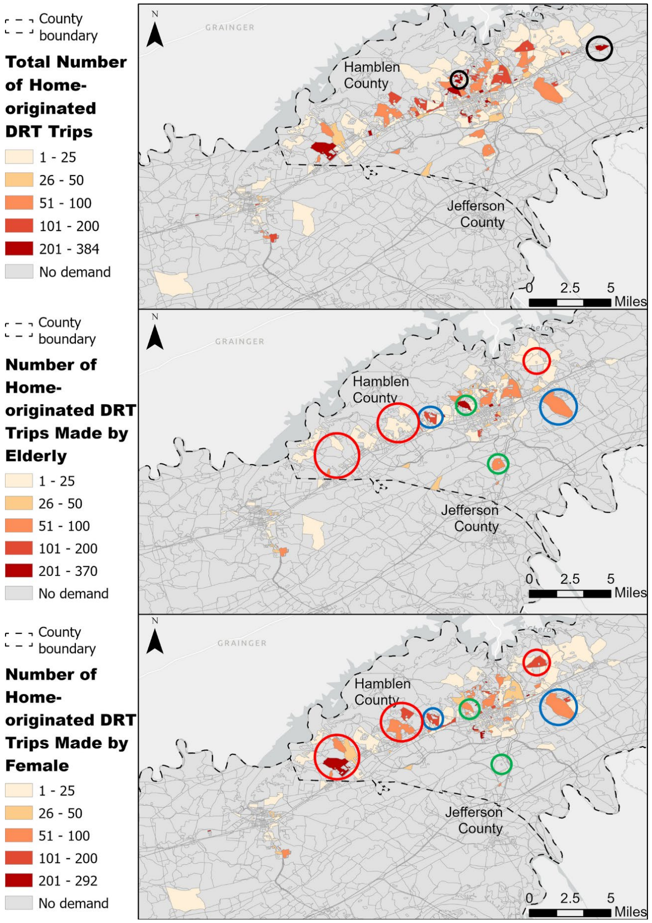


Figure 33 Spatial distribution of total DRT demand, elderly demand, and female demand represented by DRT trips

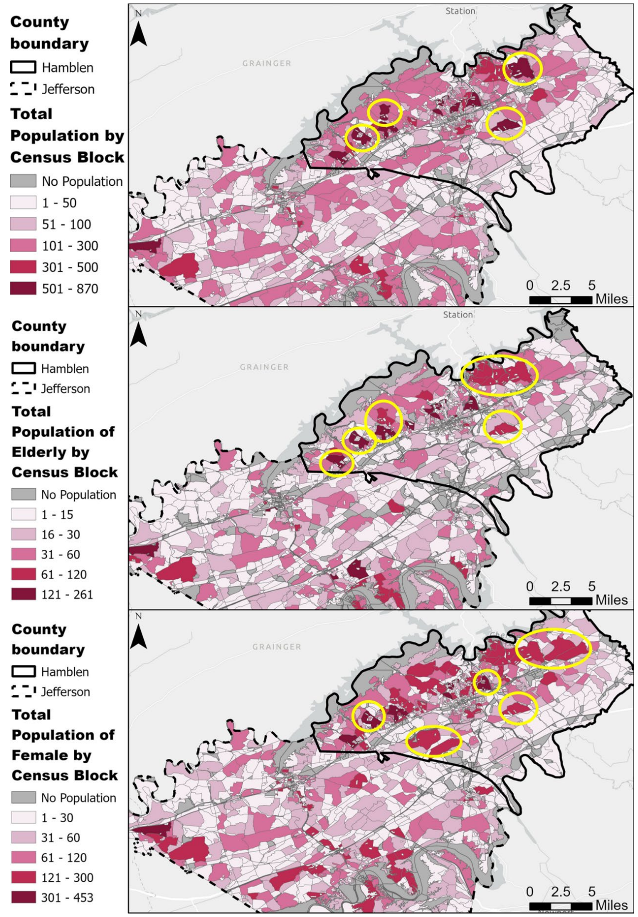


Figure 34 Spatial distribution of total population, elderly, and female from Census data

4.3.2 Spatial distribution of DRT accessibility

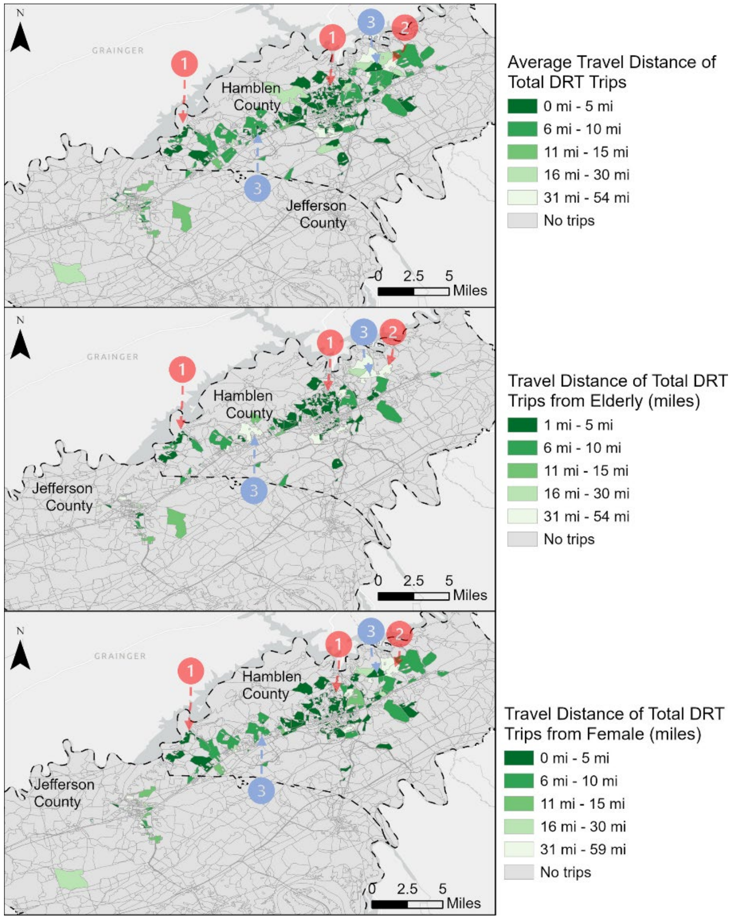
The second part analyzed the spatial distribution of DRT accessibility, as measured by the average DRT trip distance. **Figure 35** includes maps displaying the trip distances of total DRT trips and DRT trips made by females or the elderly. **Figure 36** visualizes the spatial distribution of DRT trip distance to access three essential purposes: home-healthcare (trip with destination land use of healthcare facilities), home-leisure (trip with destination land use of shopping stores and churches), and home-service (trip with destination land use of government offices and banks). These maps aimed to analyze DRT accessibility for different demographic groups (i.e., female and elderly) to essential destinations, with shorter distances indicating higher accessibility (shaded in darker green) and longer trip distances signifying lower accessibility (shaded in lighter green).

As suggested by **Figure 35** and **Figure 36**, the distribution of DRT accessibility, measured by the DRT trip distance, showed a scattered distribution. This contrasts with the more predictable accessibility trends of fixed-route transit, which typically decreases gradually from the urban center towards the city outskirts or away from fixed-route bus stops.

Figure 35 indicates that, overall, the spatial distribution of DRT trip distances in areas with both elderly and female DRT demand tends to be similar. For instance, the red symbol labeled number one highlights areas characterized by short trip distances for DRT trips made by the elderly and females, and the red symbol labeled number two highlights areas with longer trip distances for both groups. However, **Figure 35** also pinpoints a few areas where the spatial distributions of DRT trip distances differ between the elderly and females. This discrepancy is exemplified by the blue symbol labeled number three, which identified areas with shorter trip distances for females, contrasting with longer trip distances for the elderly.

To understand the spatial distribution of DRT accessibility to essential destinations, **Figure 36** illustrates the DRT trip distances for three specific trip purposes. This figure shows the locations of nearby essential destination facilities using the SafeGraph dataset within the ArcGIS tool. In general, DRT trips with different purposes showed varying spatial patterns of trip distances. Nonetheless, DRT trips to essential destinations typically displayed shorter trip distances in residential areas closer to facilities. For instance, individuals residing near Census blocks with a notable concentration of healthcare facilities tend to have shorter DRT trips, implying a potential preference for nearby healthcare facilities. Similarly, DRT passengers showed a potential trend of accessing nearby shopping stores, churches, banks, and government service locations. Leisure trips were largely concentrated within the 0-15 mile range, with no recorded trip distances falling between 16-30 miles.

To delve deeper into the identification of potential areas of concern where there was notable DRT demand (measured by the number of DRT trips) but limited DRT accessibility (assessed by DRT trip distance), the spatial relationship between DRT demand and DRT accessibility will be analyzed in the subsequent section.



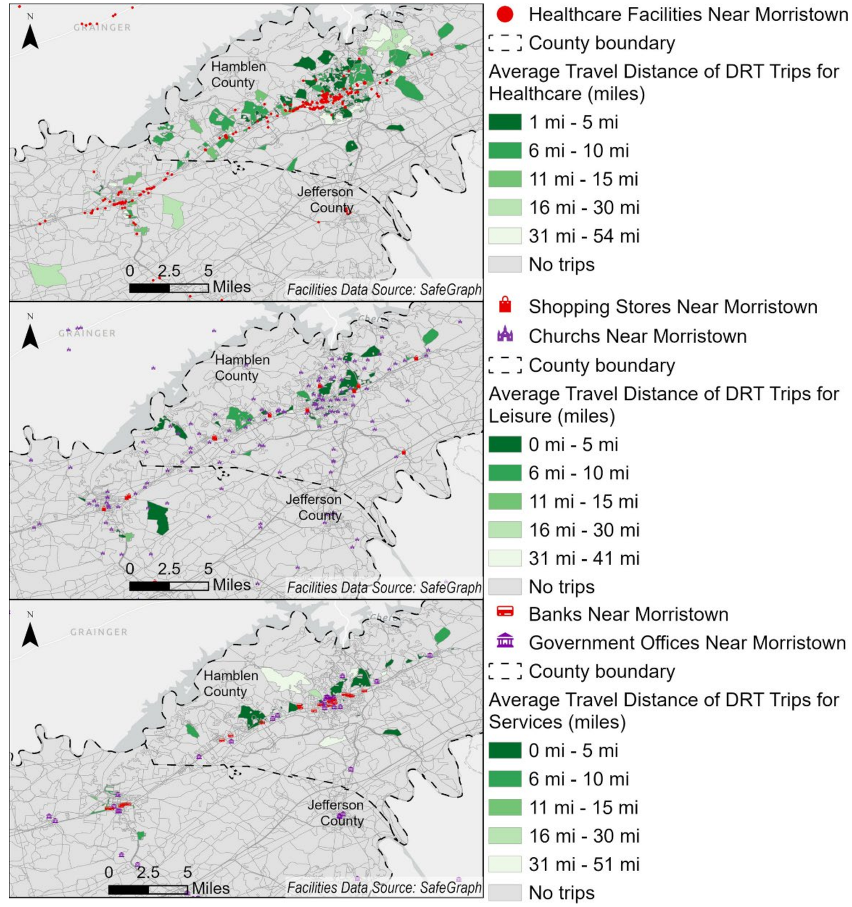


Figure 35 Spatial distribution of DRT trip distances of total trips, trips made by elderly, and trips made by female

Figure 36 Spatial distribution of DRT trip distance to access three essential destinations

4.3.3 Essential destination deserts

Census blocks were then classified based on the regional median value of DRT trips. Those with DRT trip counts equal to or below the regional median were categorized as “low demand”, while those with counts above the regional median were labeled as “high demand”. Similarly, blocks were classified as “high accessibility” or “low accessibility” depending on whether their average trip distance fell above or below the median average trip distance among all areas. Consequently, the study blocks were divided into four categories using quadrant classification and spatially visualized in **Figure 37** and **Figure 38**. These categories include “high demand-high accessibility” represented in red, “high demand-low accessibility” in pink, “low demand-high accessibility” in blue, and “low demand-low accessibility” depicted in indigo. The objective of this section is to identify the “high demand-low accessibility” areas where DRT users had limited accessibility (long travel distances) to access essential destinations, which were then categorized as potential *essential destination deserts*.

Figure 37 provides a visualization of the relationship between DRT accessibility and various DRT demand groups. Notably, certain areas have been identified as potential essential destination deserts for both the elderly and females, denoted by green circles in **Figure 37**. It was evident that there were distinct spatial variations between essential destination deserts for the elderly and for females. For instance, yellow circles show potential areas of concern for non-elderly females. These areas are identified as pink (“high demand-low accessibility”) on the bottom map but appear as indigo (“low demand-low accessibility”) in the middle map. This is due to the low demand from the elderly, even though DRT accessibility is limited. On the other hand, a purple circle highlights a Census block that is colored indigo on the middle map but appears in red on the bottom map. This signifies that this specific Census block exhibits high demand from females who also have higher accessibility levels. However, in this area, there is low demand from the elderly, who similarly experience long travel distances to access their destinations.

Moving beyond DRT accessibility for specific demographic groups, **Figure 38** delved into the spatial analysis of DRT accessibility to access three essential destinations (based on destination lane use) for total DRT demand. In **Figure 38**, Census blocks marked in pink indicate areas characterized by high DRT demand but limited accessibility for accessing healthcare facilities, shopping stores, churches, bank services, and government services.

As **Figure 38** illustrates, Census blocks highlighted by green circles were classified as “high demand-low accessibility” (pink areas) for healthcare and leisure trips while they were classified as “high demand-high accessibility” (red areas) for services-seeking trips. This suggests that in these areas, despite having a high demand for all three essential destinations, they only have higher levels of accessibility for service destinations (i.e., government services and banks). However, the accessibility to healthcare and leisure destinations was lower than the regional median. Two Census blocks are highlighted in **Figure 38** with a yellow and purple circle, respectively. These blocks had relatively high DRT accessibility to both healthcare and leisure destinations. However, due to the blocks having higher demand solely for healthcare trips, they were categorized as healthcare deserts and classified as “low demand-low accessibility” for leisure trips. The block encircled by a yellow circle displayed a low accessibility to banks and government services, whereas the block encircled by a purple circle had a higher accessibility to these destinations, even though both blocks had demand for these trips lower than the regional median.

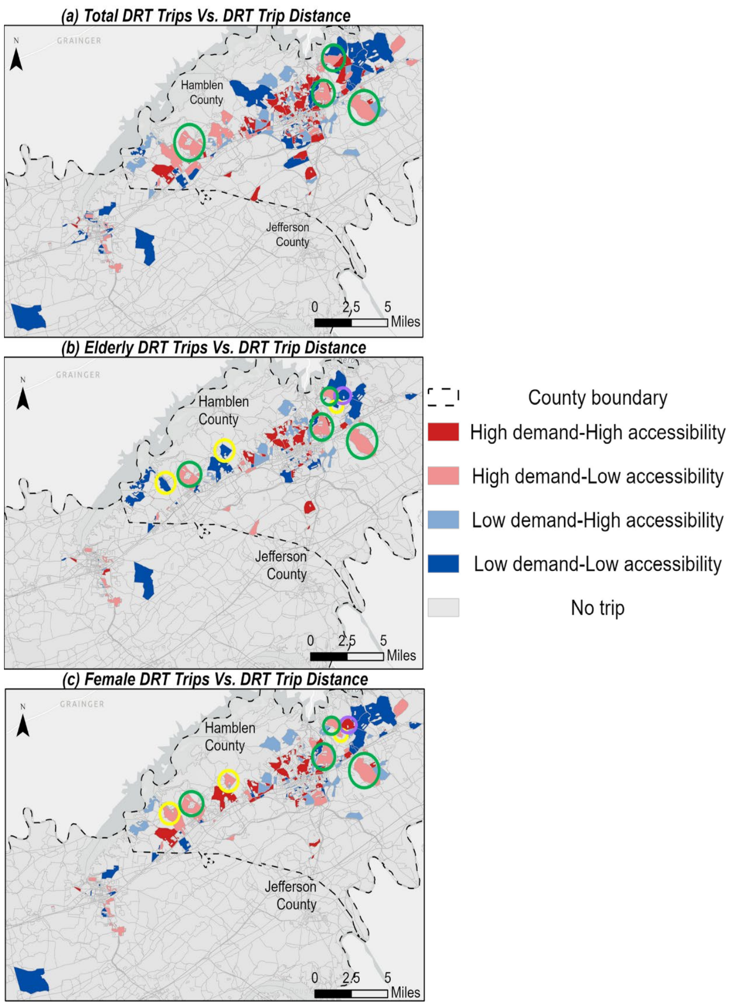


Figure 37 Spatial distribution of the relationship between different DRT demand types and DRT trip distance

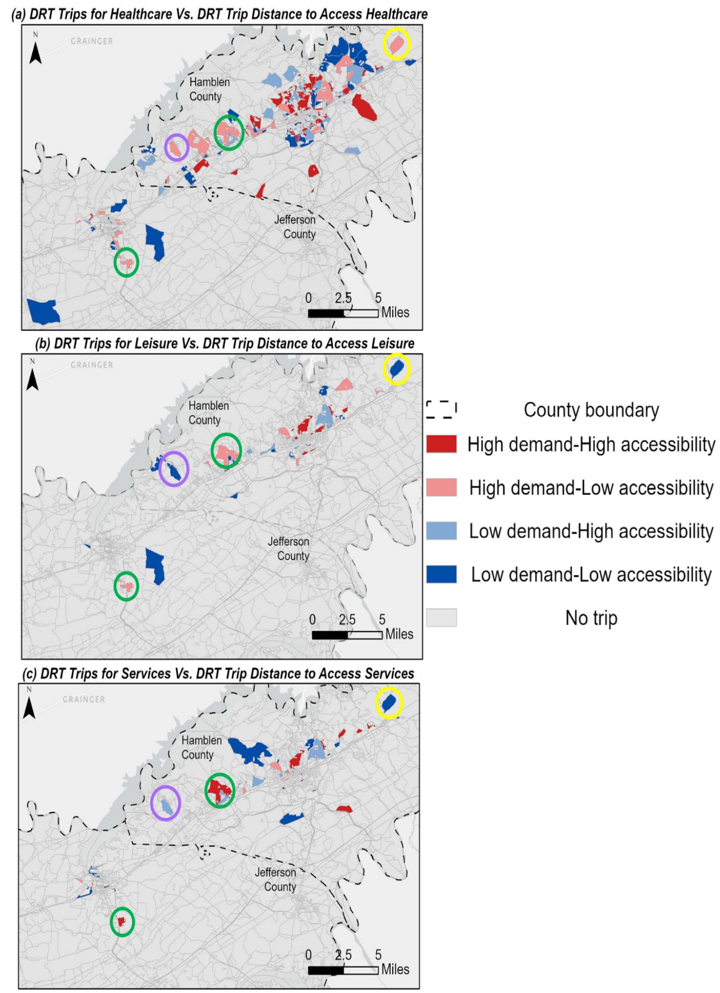


Figure 38 Spatial distribution of the relationship between DRT demand and DRT trip distance to access different essential destinations

Chapter 5 Conclusion and Future Research

This chapter presents conclusions, areas for future research, and recommendations for the Tennessee Department of Transportation and local transit agencies in Nashville, Memphis, Knoxville, Chattanooga, and Morristown based on the research findings.

5.1 Conclusions

This section presents a brief summary of the key findings from the FRT analyses and DRT analysis. First, this project evaluated FRT accessibility and equity to essential services in four major urban cities in Tennessee: Nashville, Memphis, Knoxville, Chattanooga. The analysis of the temporal transit accessibility revealed that FRT services in the four cities exhibit low variance across various time periods of the day. Following that, a visualization was created to analyze the spatial distribution of the transit supply index and transit demand index. The spatial distribution of the transit supply index to parks was different from that of food, healthcare, school, and childcare in Nashville. In the other three cities, the transit supply index to healthcare was different from that of food, school, childcare, and parks; Memphis, Knoxville and Chattanooga each had numerous areas with limited transit accessibility to healthcare facilities, but they featured relatively evenly distributed transit accessibility to the other four essential services (food stores, schools, childcare, and parks).

Based on the maps of the transit demand index, many areas in Nashville exhibited relatively low levels of potential demand for transit. In Memphis, higher demand was observed from minority populations. Chattanooga, on the other hand, exhibited a similar distribution of transit demand among car-limited, poverty, and minority populations, suggesting a potential overlap among these three groups. In Knoxville, there were some areas where an overlap exists among different groups (e.g., car-limited, those in poverty, and/or minority groups).

The bi-LISA spatial clustering further identified essential service deserts and indicated that different spatial distributions of essential service deserts were observed across cities. In Nashville, areas with high potential transit demand were more likely to have limited transit access to food stores, healthcare, school, and childcare categories than to have limited transit access to parks. Most essential service deserts were notably concentrated in the north edge of Chattanooga. When conducting a cross-sectional comparison in Memphis, there was only a slight difference in transit supply to access specific essential services for different demand groups. This might result from the fact that transit demand in the three population groups exhibits a similar spatial distribution. Knoxville had some essential service deserts positioned closer to the city center; however, in terms of the count of essential service deserts, Knoxville had the least number of deserts compared to other cities.

Last, the research proposed a method to measure DRT accessibility and to identify potential essential destination deserts by analyzing the relationship between DRT trip demand and DRT accessibility in Morristown. A quadrant classification was used to identify potential areas of concern with limited DRT accessibility and high DRT trip demand in Morristown. The results identified “essential destination deserts” and revealed distinct spatial variations between some demographic groups (the elderly and females). The classification results also illustrated certain areas displaying varying spatial relationships between DRT demand and DRT accessibility when accessing different essential destinations (i.e., healthcare, leisure, and service destinations).

5.2 Recommendations

Recommendation 1: Consider fixed route transit service modifications or add essential service facilities in essential service deserts, particularly for accessing healthcare

The findings of the spatial FRT accessibility analysis and the identification of transit deserts of essential services can help transit agencies and local planning departments to prioritize their resources and target interventions to improve transit access to essential services for specific populations. For instance, the results revealed a greater level of transit inequity towards healthcare facilities compared to other essential services in all four cities. This finding underscores the importance for transit authorities to prioritize connections with healthcare facilities when formulating transit planning decisions. Additionally, the identification of different categories of essential service deserts through the clustering map provides a valuable resource for developing and implementing customized urban planning and transit planning strategies. For example, the analysis identified that in the mid-northwest areas of Nashville, minority populations have more limited transit access to all five essential services, necessitating efforts to improve transit access to all five categories of essential services or to locate more of these essential service facilities in the mid-northwest Nashville.

Recommendation 2: Improve DRT services or add facilities in potential essential destination deserts in small urban areas

The findings of spatial DRT accessibility analysis and the identification of potential essential destination deserts can help transit operators and local planning departments to prioritize their resources and target interventions to improve DRT services. Based on the identification of potential essential destination deserts for specific demographic groups, DRT operators can enhance their services accordingly. In instances where areas are characterized by significant spatial distances to an essential destination category, local urban planning departments may explore the option of incentivizing additional service facilities to address these distance-related challenges. In addition, DRT operators can implement various measures to address areas with longer DRT travel distances to access the destination. For instance, optimizing route planning to minimize travel time, increasing the frequency of DRT services in these areas, and/or exploring partnerships with local businesses or community centers to establish pickup points or stops can potentially improve accessibility. Furthermore, incorporating technology solutions, such as real-time tracking and scheduling apps, may improve the convenience of DRT services in areas with extended travel distances.

5.3 Areas for Future Research

Area for Future Research 1: Conduct surveys of actual travel behaviors and travel preferences to enhance the precision of the accessibility analysis

Fixed route transit accessibility was estimated under the assumption that individuals choose to access the nearest essential service location; however, people may choose differently based on other criteria (e.g., a facility that is located farther away but is preferred for other reasons). Consequently, the identification of transit deserts represents a potential supply-demand mismatch. Future research using actual behavioral data from surveys could enhance the precision of the accessibility analysis.

Area for Future Research 2: Expand the accessibility analyses to other demographic groups

Future research could expand upon this study's focus on transit equity for car-limited, poverty, and minority populations by including an examination of fixed route transit accessibility for seniors or individuals with disabilities. This would contribute to a more comprehensive understanding of transit equity of FRT across a broader range of vulnerable and underserved populations.

For the demand response transit (DRT) analysis, this research was limited to age and gender due to the availability of this demographic information in the dataset. For a broader analysis of DRT usage purposes, it would be valuable to investigate other demographic factors, such as disability status, income level, and car ownership, in future research.

Area for Future Research 3: Apply the DRT accessibility method to a more rural area

The demand response transit (DRT) accessibility analysis in this report focused on the small urban area of Morristown, TN. This area was selected for analysis because of the availability of high-quality DRT trip data that included the approximate home location of the trip-maker. In the future, the DRT accessibility method could be applied to rural areas of Tennessee if DRT trip datasets include the approximate home location of the traveler, which can then be used to evaluate home-based DRT trips.

Area for Future Research 4: Evaluate transit accessibility with a combination of FRT and DRT

This research assessed accessibility of fixed route transit and demand response transit systems separately. A potential future research direction could consider both fixed route and demand response transit together to examine overall transit accessibility levels. Such an approach would provide insights into transit accessibility at the intersection of these two modes, further enriching accessibility analysis by considering multiple transit services.

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Appendices

Appendix 1: Data and method for DRT analysis

Table 2 Variables creation and explanation

Category	Explanation	Count (%)
Gender	Passengers identified themselves as male or female. NA or "prefer not to say" records were removed from analysis.	
Male		10,606 (46.79%)
Female		12,063 (53.21%)
Age groups	Passenger age range: [0 – 97] years old	
Children	Passengers aged between 0-12 years old	50 (0.22%)
Adolescent	Passengers aged between 13-18 years old	167 (0.74%)
Young Adult	Passengers aged between 19-29 years old	1,616 (7.13%)
Adult	Passengers aged between 30-64 years old	12,693 (55.99%)
Elderly	Passengers aged 65+ years old	8,143 (35.92%)
Time segments	Time range: 5 a.m. to 6 p.m.	
Early morning	Trips start between 5 a.m. to 6 a.m.	1,589 (7.01%)
AM peak	Trips start between 7 a.m. to 9 a.m.	5,736 (25.3%)
Midday	Trips start between 10 a.m. to 3 p.m.	11,783 (51.98%)
PM peak	Trips start between 4 p.m. to 6 p.m.	3,561 (15.71%)
Distance segments	Distance range: (0-89.42] miles	
Short distance	The trip distance falls within the first quartile (Q1) range (shortest distance to the median length of distance).	5,751 (25.37%)
Median-short distance	The trip distance falls within the second quartile (Q2) range (between the 25th and 50th percentiles of all recorded distances).	5,592 (24.67%)
Median-long distance	The trip distance falls within the third quartile (Q3) range (between the 50th and 75th percentiles of all recorded distances).	5,658 (24.96%)
Long distance	The trip distance falls within the fourth quartile (Q4) range (between the 75th percentile and the maximum value of the distances).	5,668 (25%)

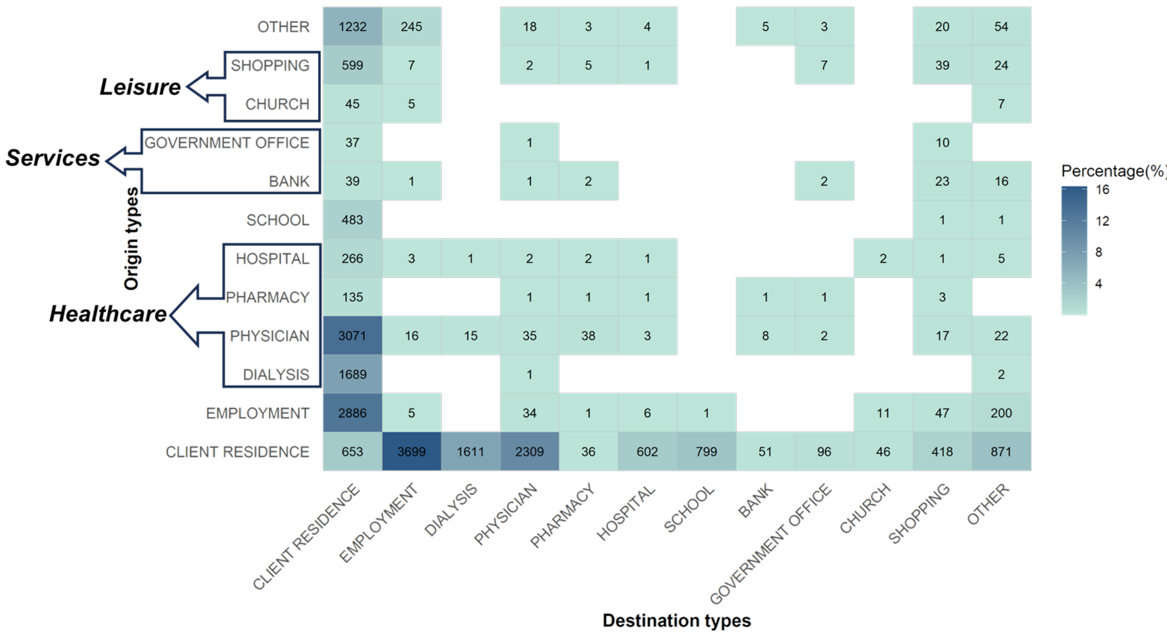


Figure 39 Heatmap for trips with different types of origins and destinations

Table 3 Types and trip purpose classification

Trip types	Trip purpose	Explanation	Count	Percent (%)
HBW	Home-Work	Employment trips from (to) the client's residence	6,585	29.05%
HBO	Home-Healthcare	Trips from (to) hospitals, pharmacies, physicians, or dialysis places to (from) client residences.	9,719	42.87%
	Home-Home	Trips with both origin and destination being different client residences, recognized as home-visit trips	653	2.88%
	Home-Leisure	Trips from (to) churches or shopping places to (from) client residences	1,108	4.89%
	Home-School	Trips from (to) schools to (from) client residences	1,282	5.66%
	Home-Service	Trips from (to) banks or government offices to (from) client residences	223	0.98%
	Home-Other	Trips from (to) “other” to (from) client residences	2,103	9.28%
NHB	Non-Home-Healthcare	Trips from origins besides client residences to hospitals, pharmacies, physicians, or dialysis places	179	0.79%
	Non-Home-Leisure	Trips from origins besides client residences to churches or shopping places	174	0.77%
	Non-Home-School	Trips from origins besides client residences to schools	1	0.00%
	Non-Home-Service	Trips from origins besides client residences to banks or government offices	29	0.13%
	Non-Home-Other	Trips from origins besides client residences to “other”	331	1.46%
	Non-Home-Work	Employment trips from origins besides client residences	282	1.24%
Total			22,669	100%

Appendix 2: Scatter plots and box plots in other three cities

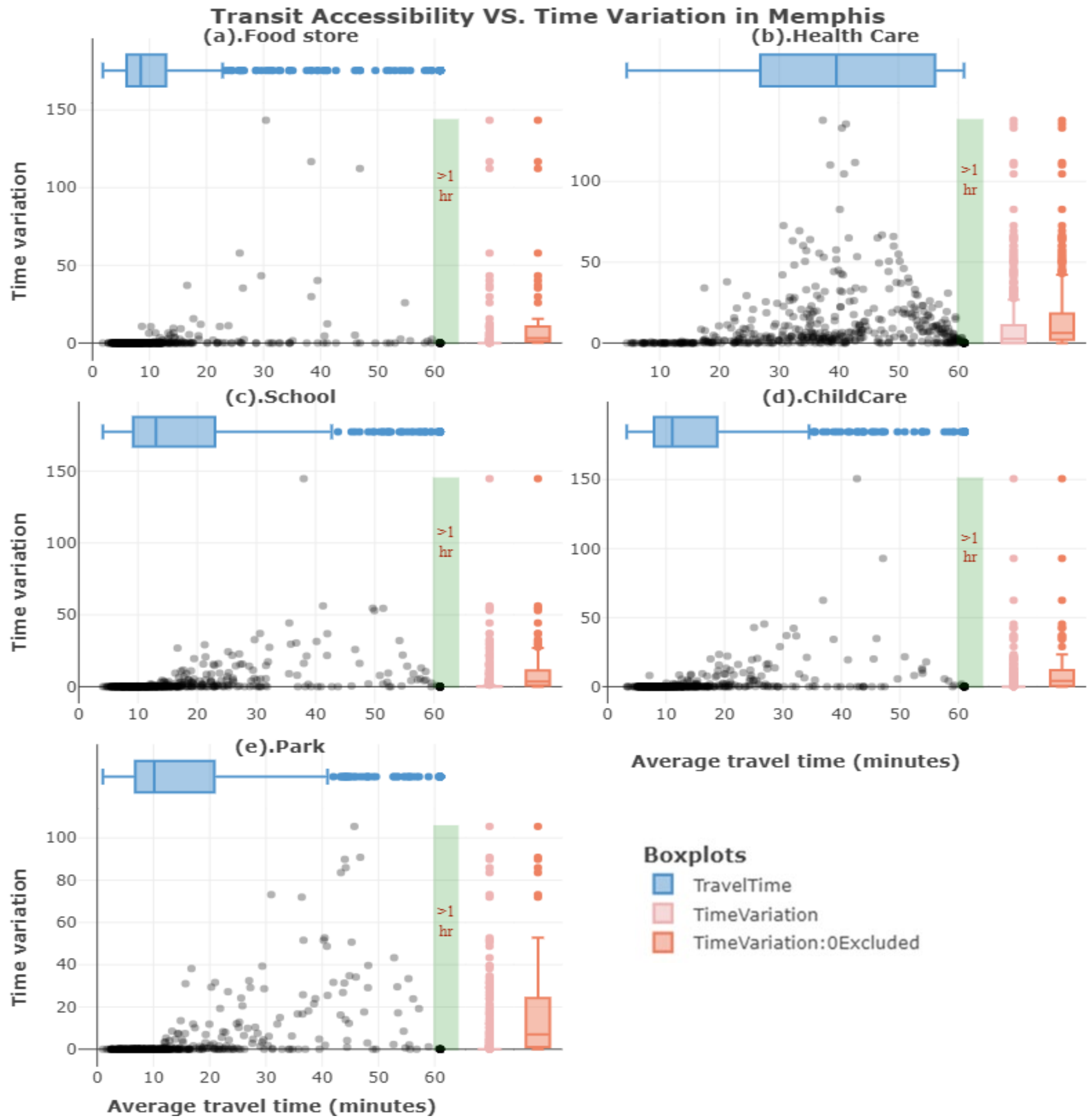


Figure 40 Scatter plots and box plots of transit accessibility and time variation in Memphis

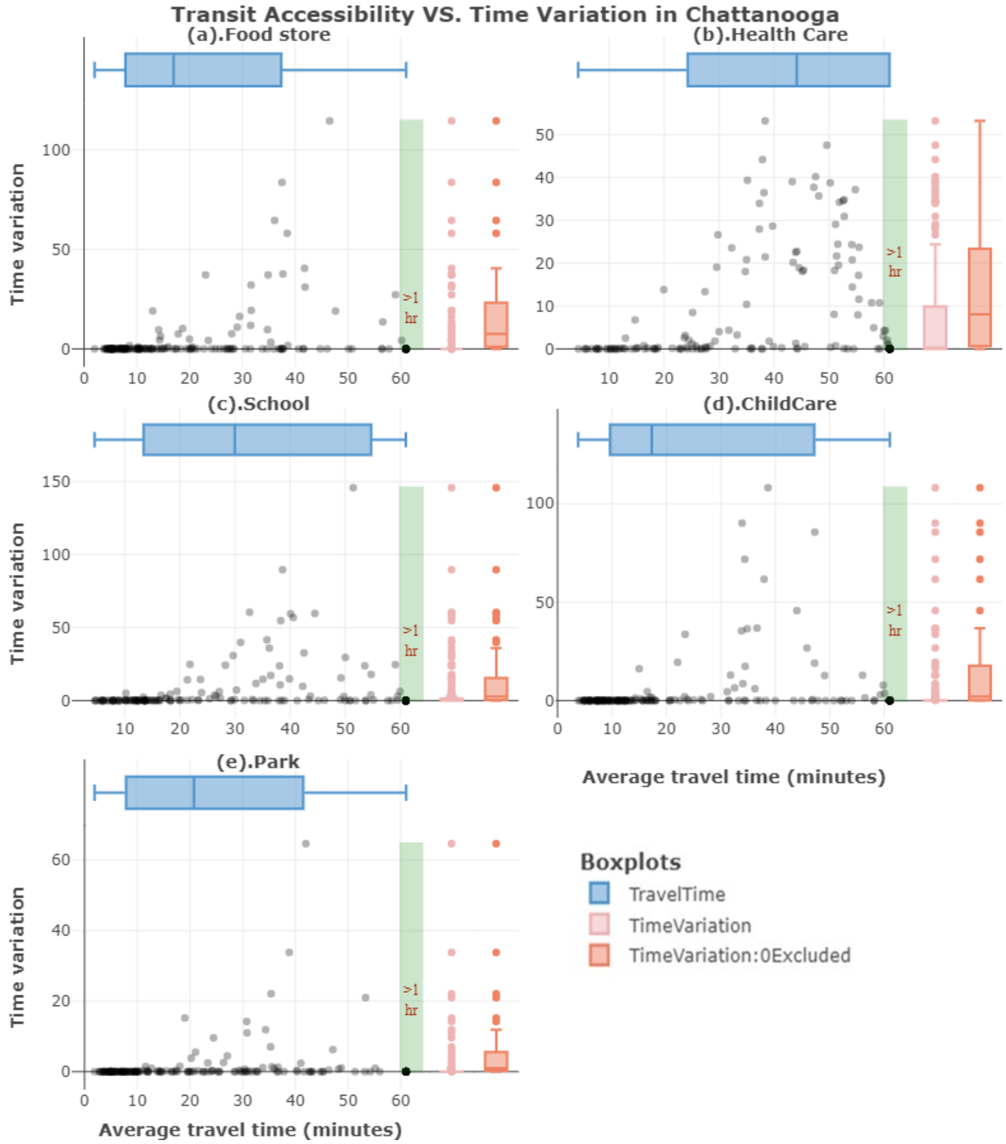


Figure 41 Scatter plots and box plots of transit accessibility and time variation in Chattanooga

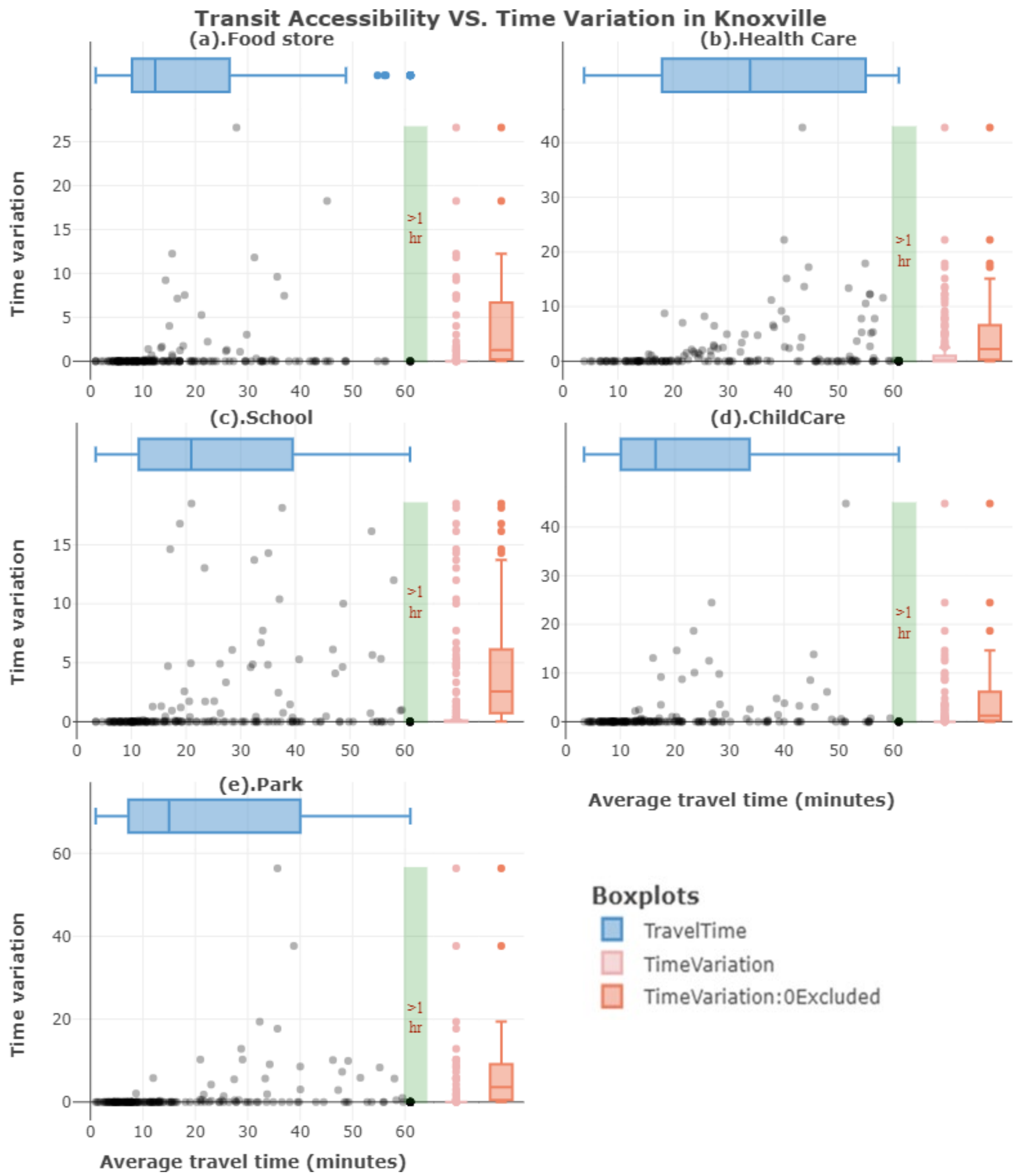
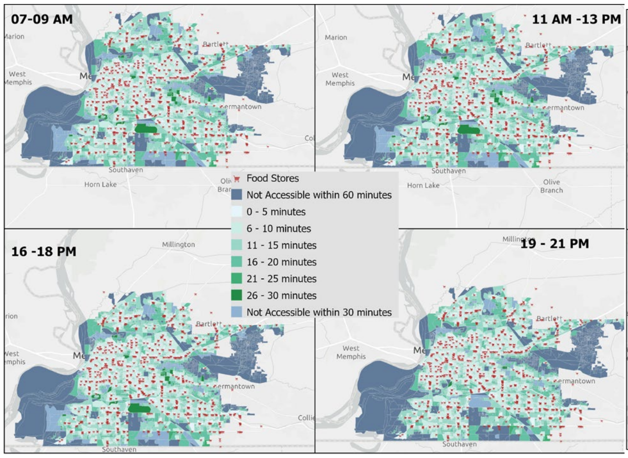
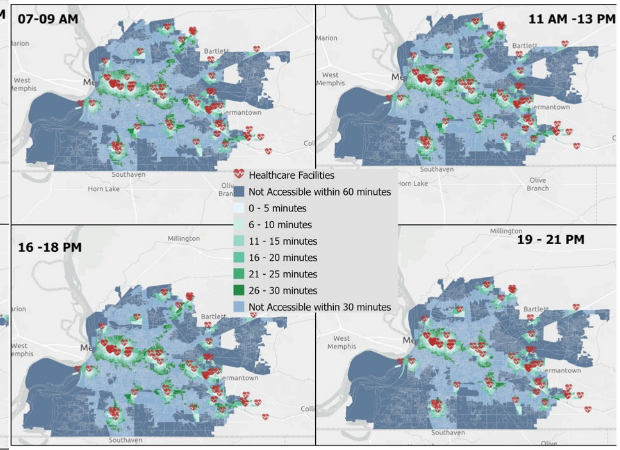


Figure 42 Scatter plots and box plots of transit accessibility and time variation in Knoxville

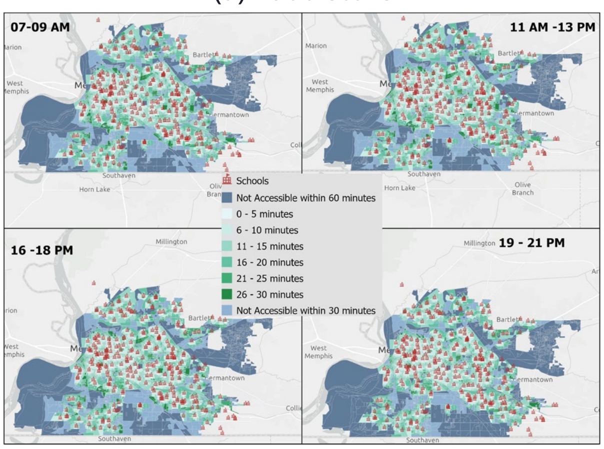
Appendix 3: Transit travel time to access the nearest essential service facility in Memphis, Chattanooga, and Knoxville



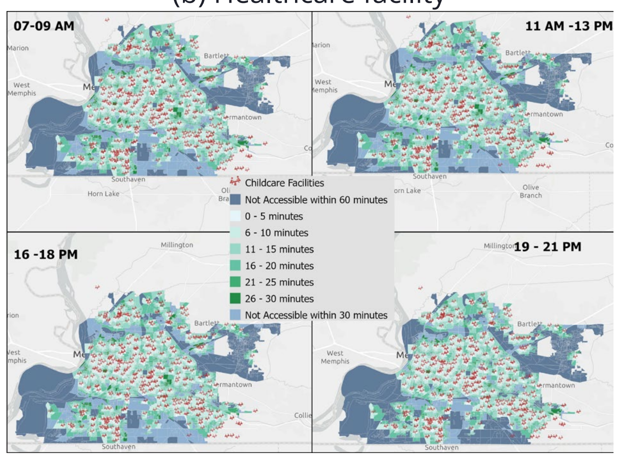
(a) Food store



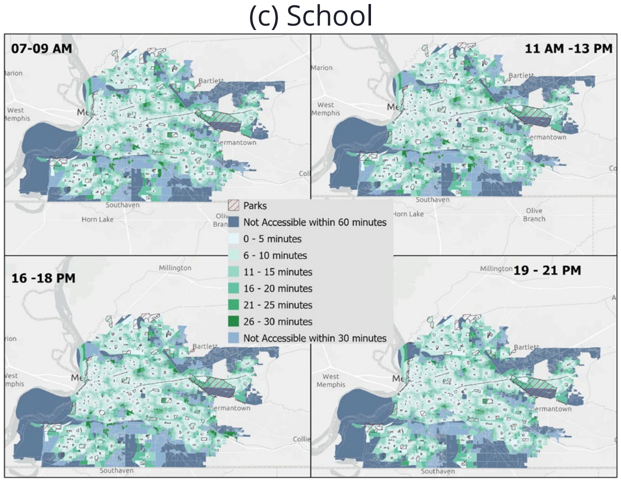
(b) Healthcare facility



(c) School

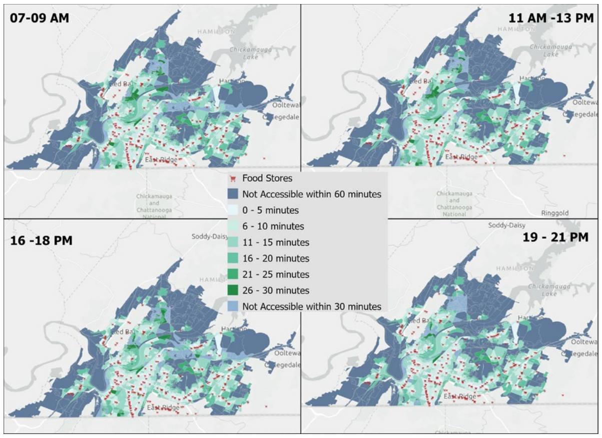


(d) Childcare facility

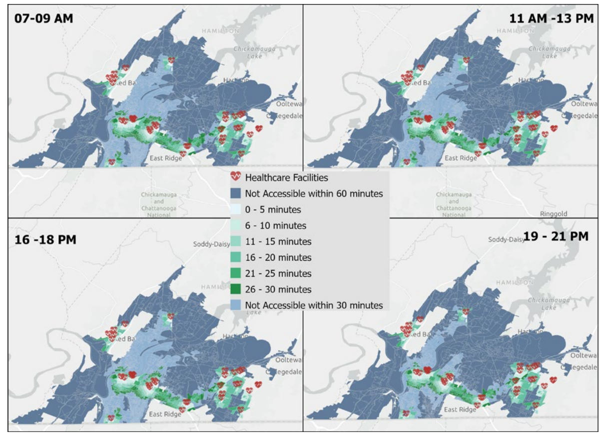


(e) Park

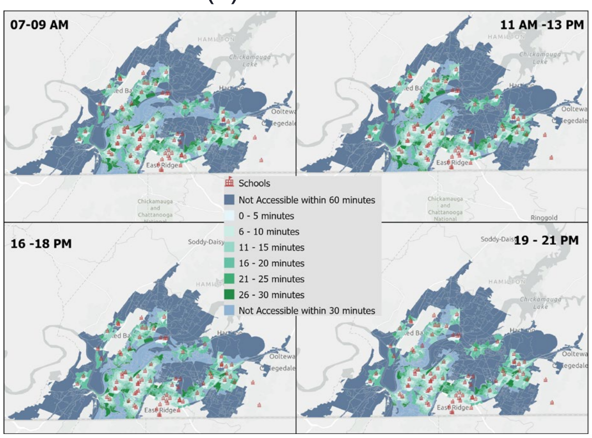
Figure 43 Travel time to access the nearest essential service facility in Memphis



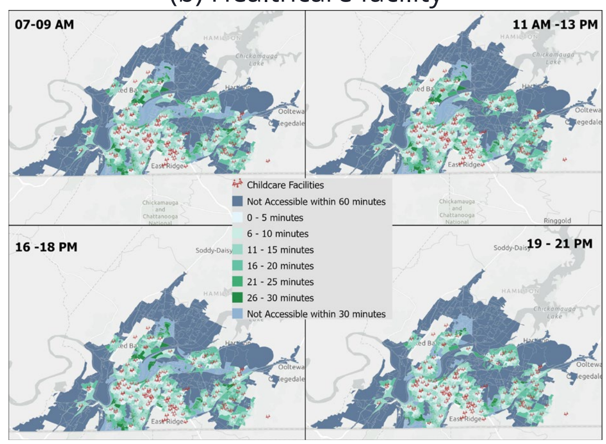
(a) Food store



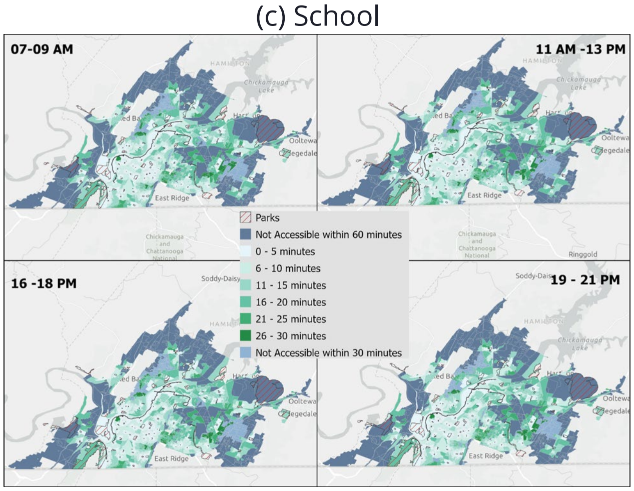
(b) Healthcare facility



(c) School

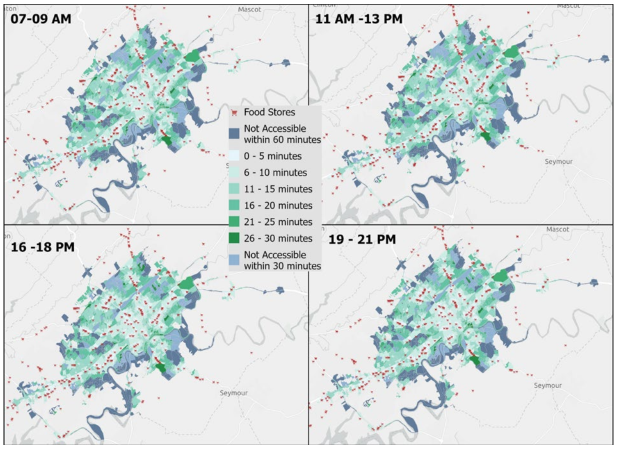


(d) Childcare facility

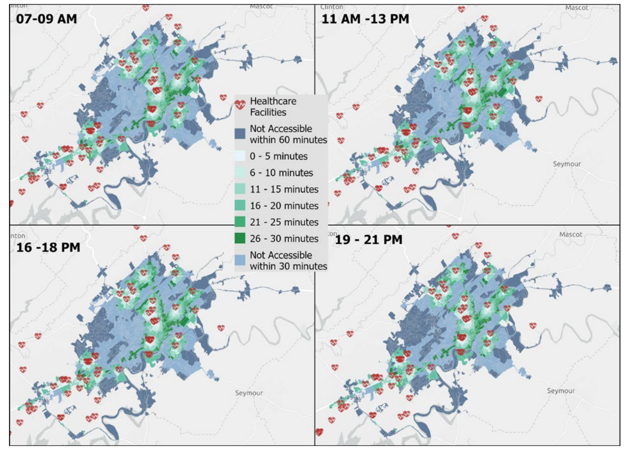


(e) Park

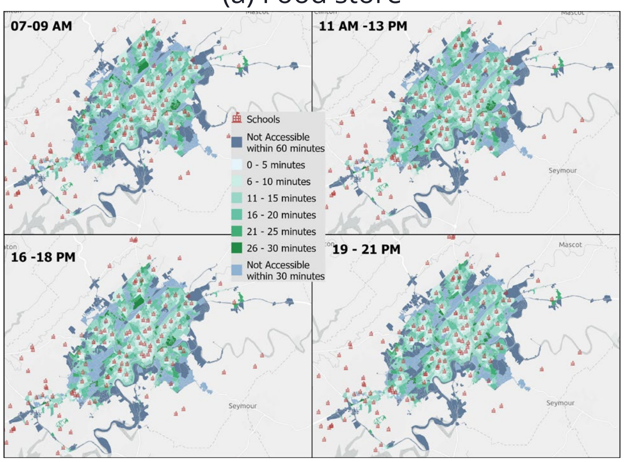
Figure 44 Travel time to access the nearest essential service facility in Chattanooga



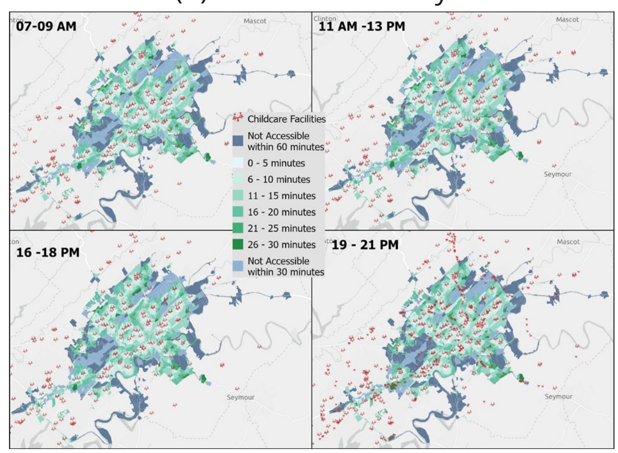
(a) Food store



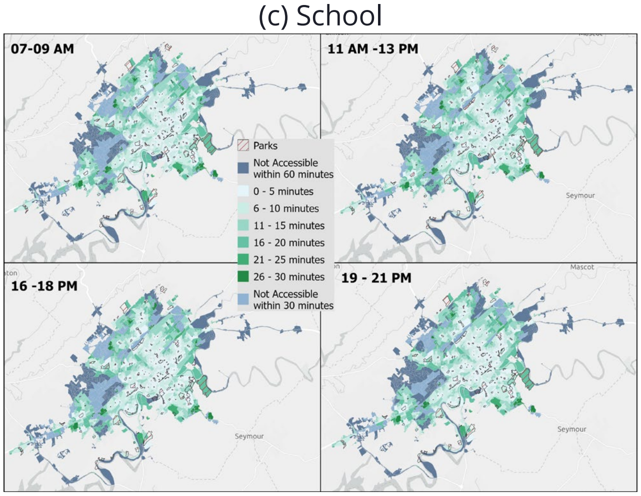
(b) Healthcare facility



(c) School



(d) Childcare facility



(e) Park

Figure 45 Travel time to access the nearest essential service facility in Knoxville

Appendix 4: Transit demand index in Memphis, Chattanooga, and Knoxville

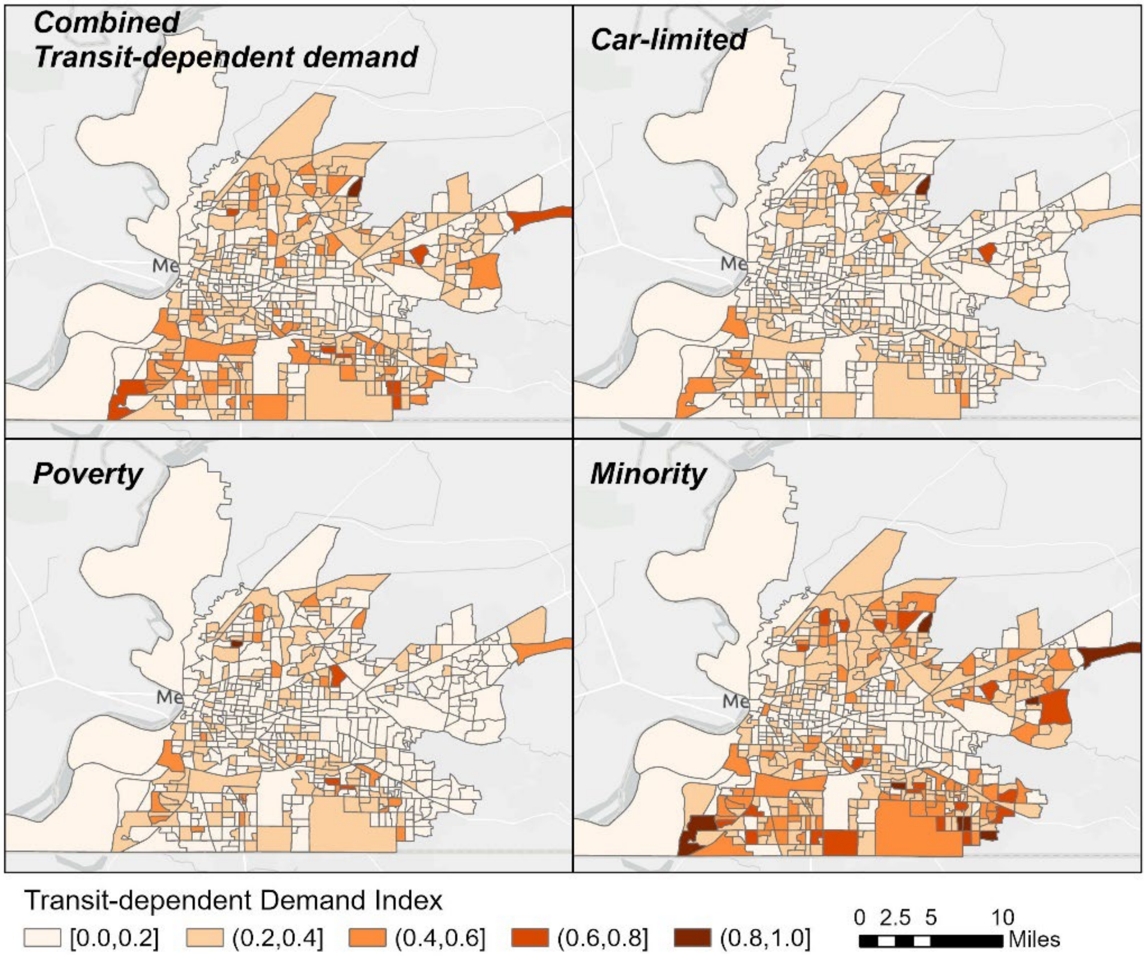


Figure 46 Distribution of the transit demand index in Memphis

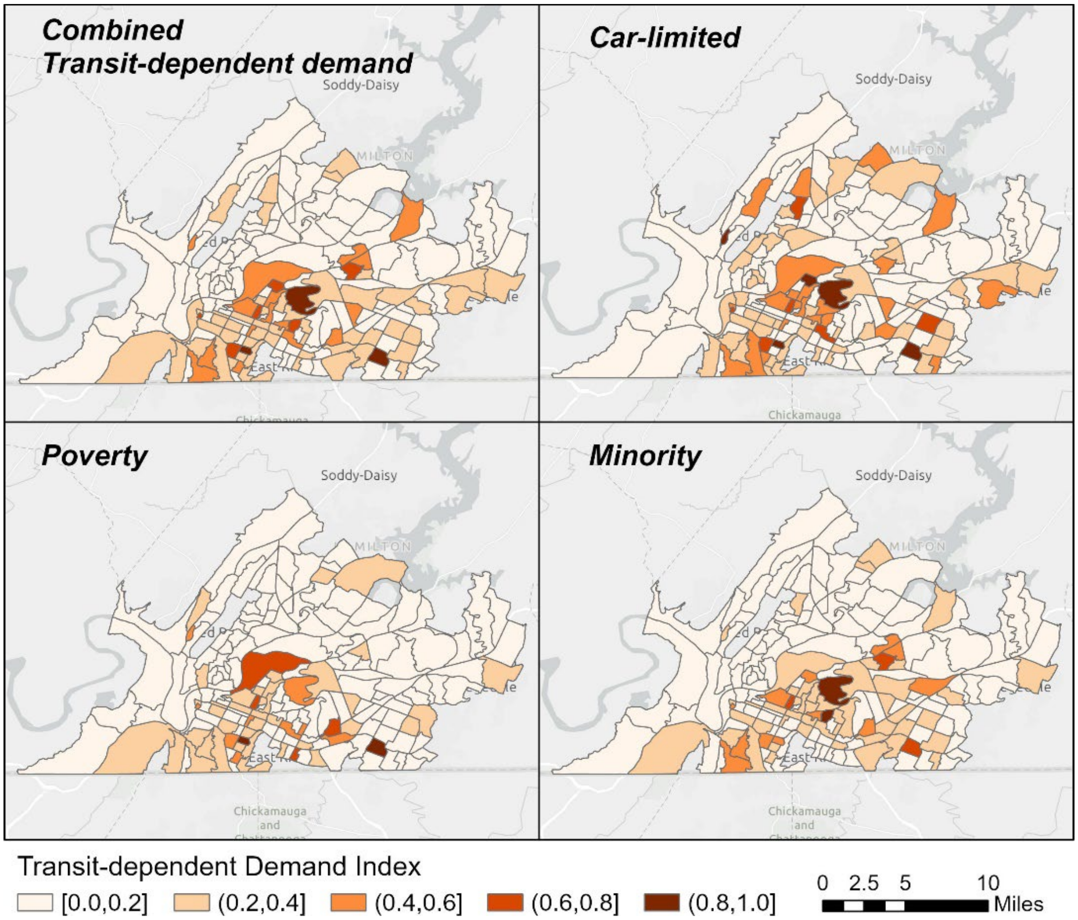


Figure 47 Distribution of the transit demand index in Chattanooga

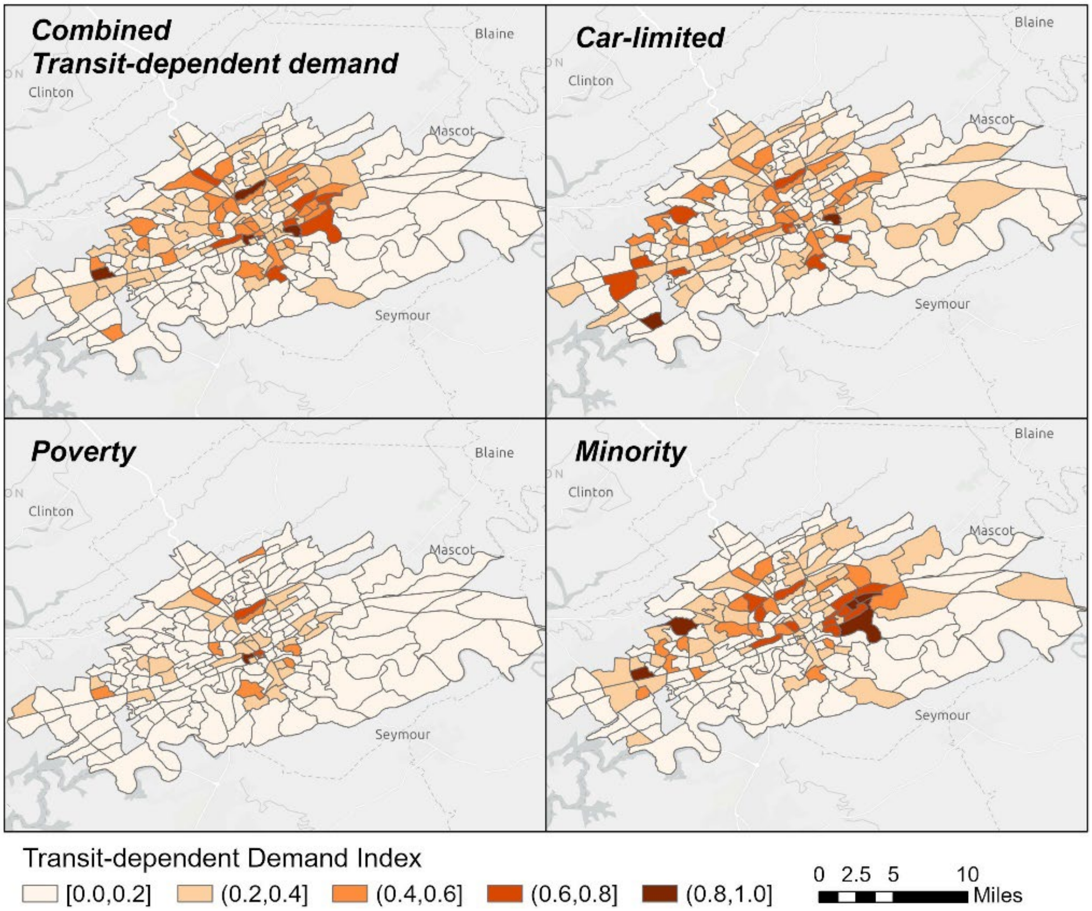


Figure 48 Distribution of the transit demand index in Knoxville

Appendix 5: Bi-LISA bar charts in Nashville, Memphis, Chattanooga, and Knoxville

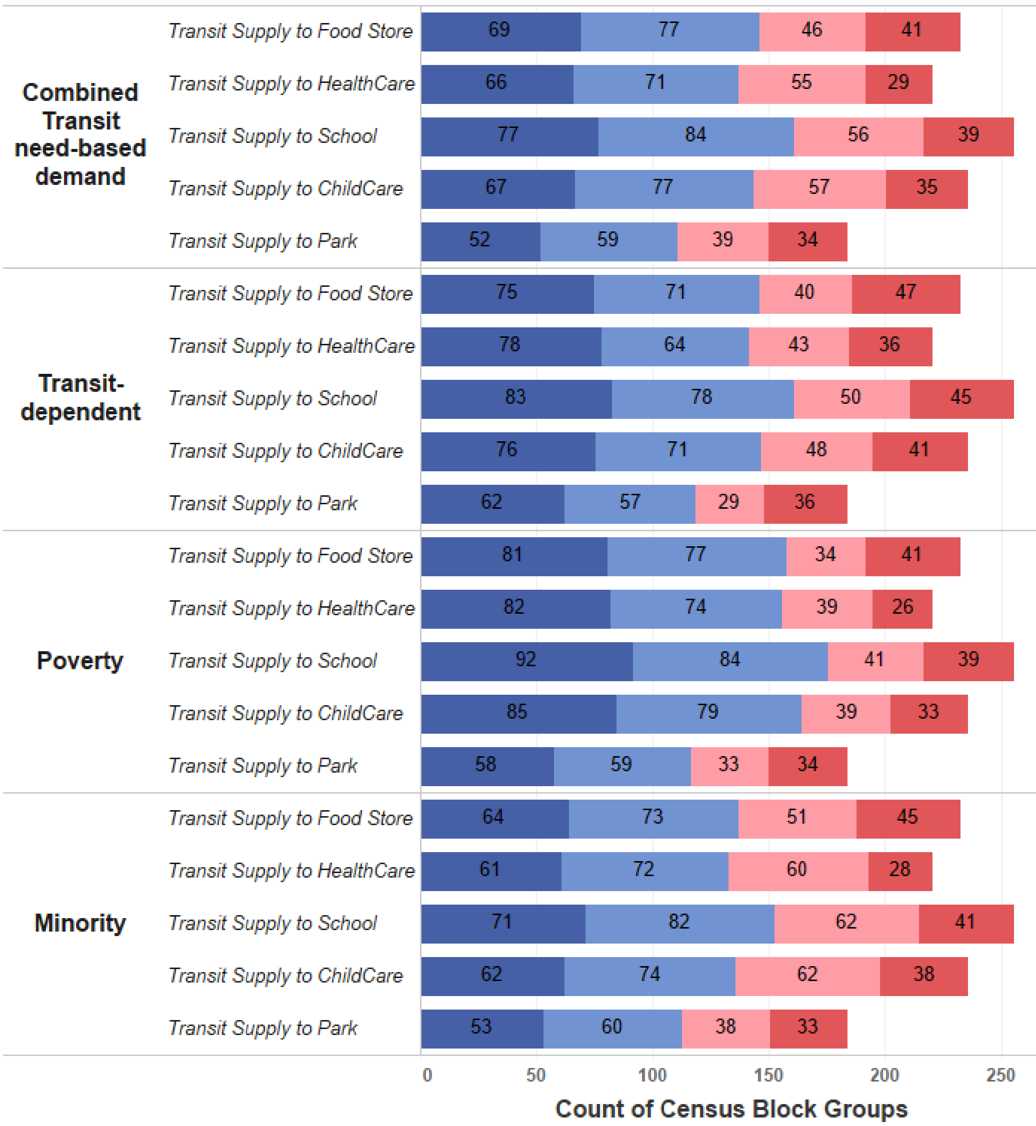


Figure 49 Bar plot of summary of bi-LISA clusters in Nashville

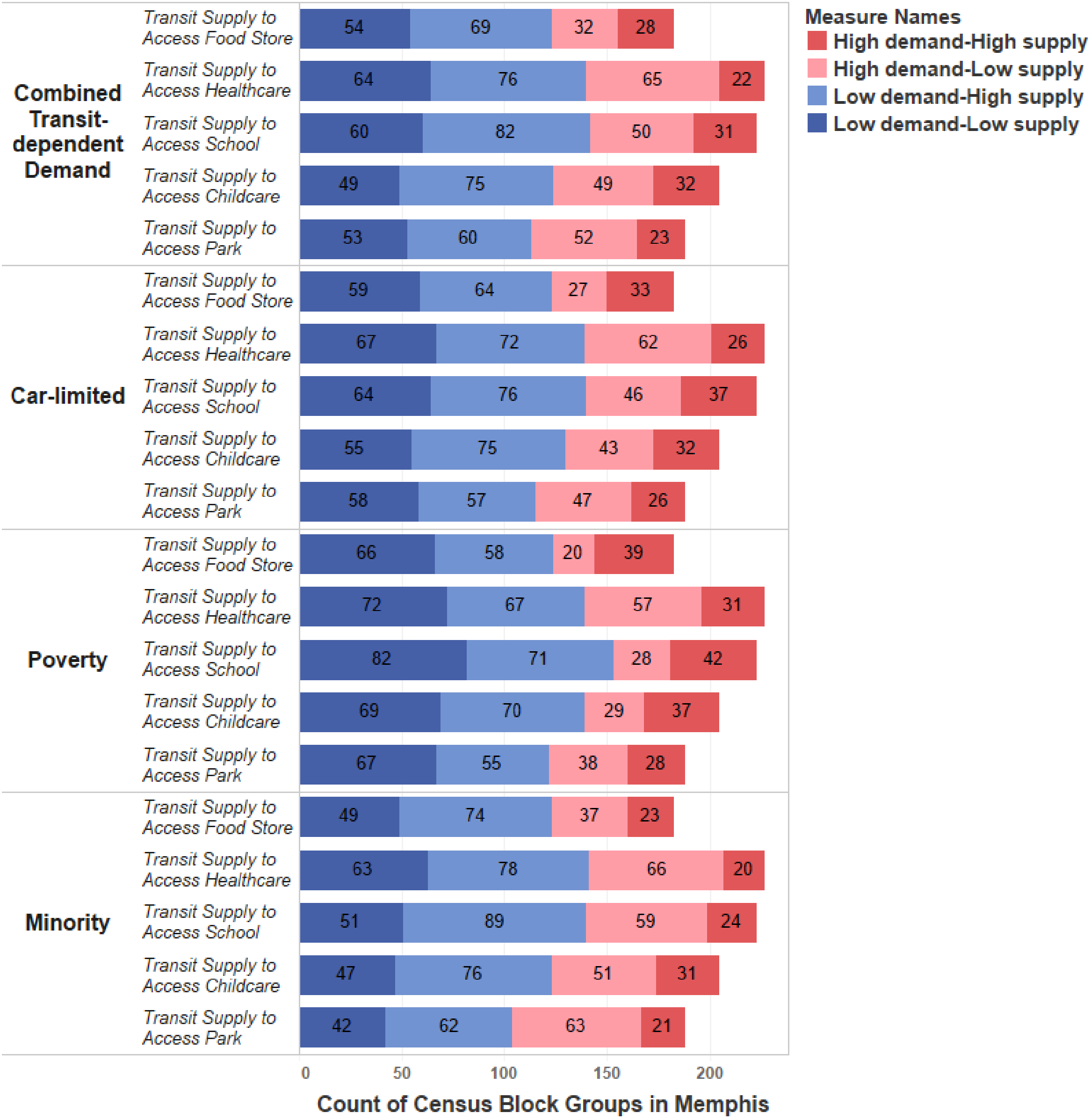


Figure 50 Bar plot of summary of bi-LISA clusters in Memphis

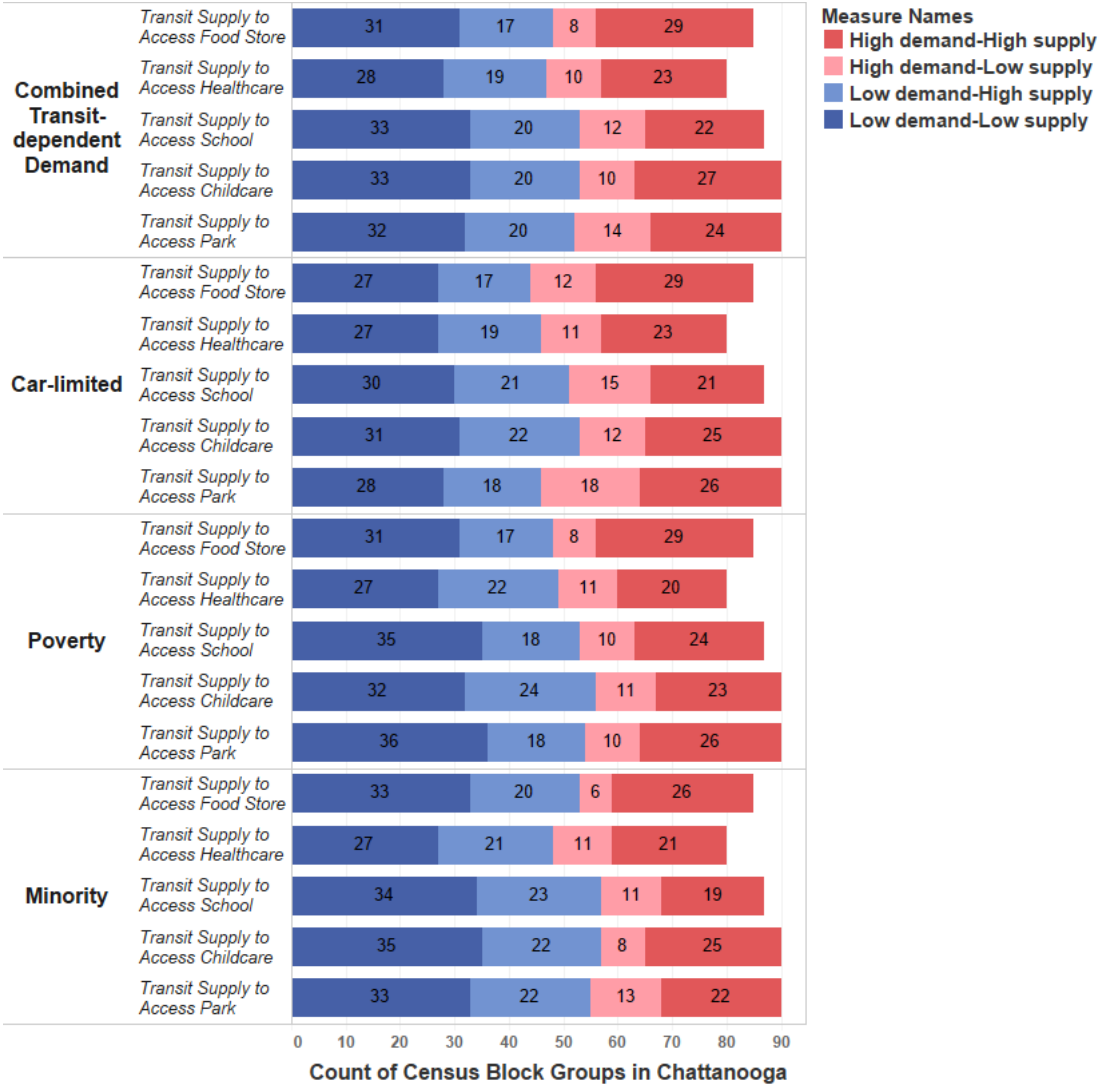


Figure 51 Bar plot of summary of bi-LISA clusters in Chattanooga

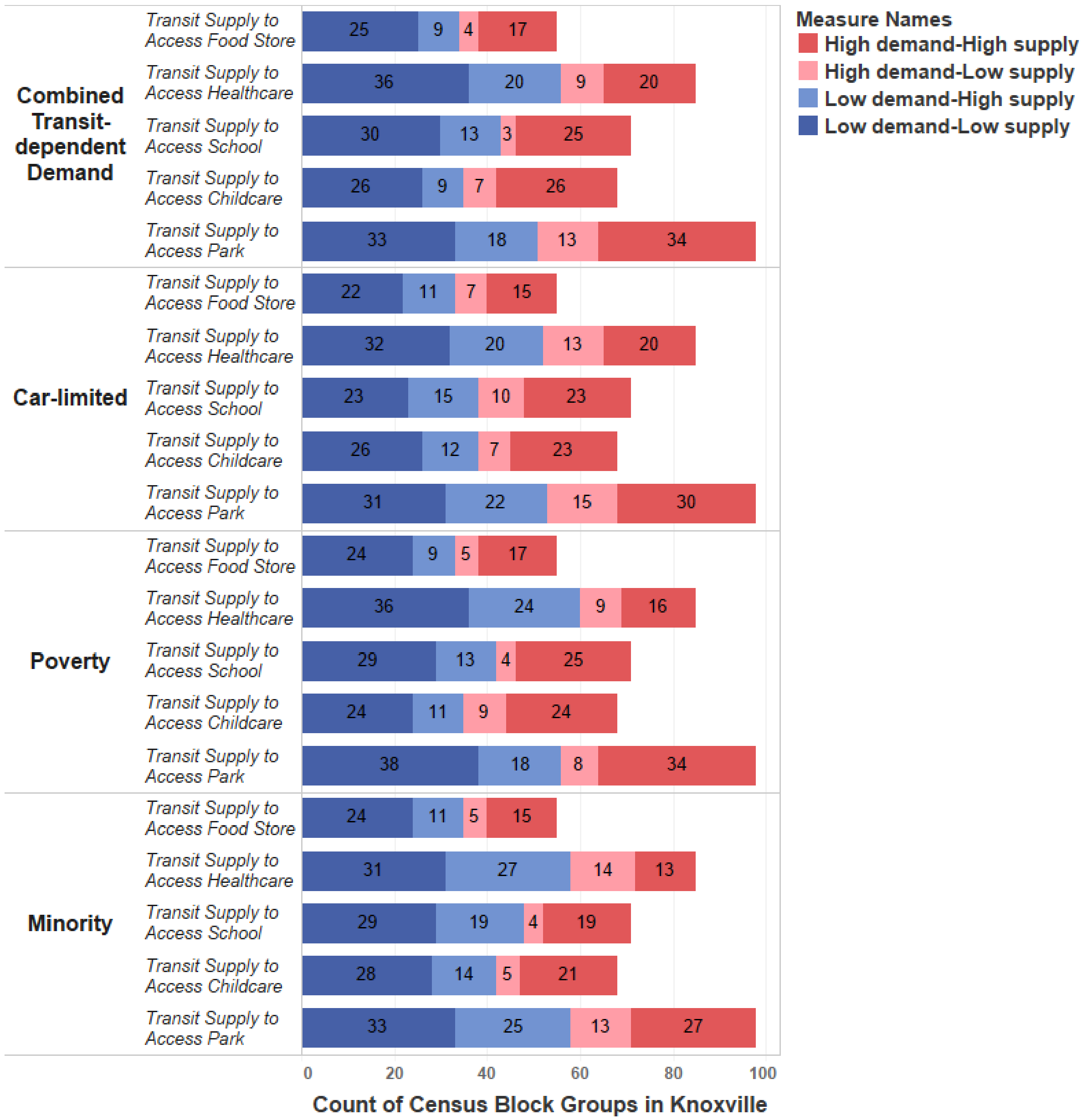


Figure 52 Bar plot of summary of bi-LISA clusters in Knoxville