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Equity and accessibility assessment of fixed route transit systems integrated with on-demand feeder services

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ABSTRACT

In contemporary societies, public transportation holds paramount significance for fostering sustainable and equitable urban development. Concurrently, innovative mobility solutions, such as the integration of on-demand mobility services like Demand Response Transit (DRT) and Transportation Network Companies (TNC) with Fixed Route Transit (FRT) systems, are gaining prominence. On-demand mobility, with its adaptive dynamic routing, can improve public transit access by best utilizing the existing infrastructure. However, to ensure the adequacy of the service of an integrated system, it is essential to evaluate equity and accessibility of the system. While research has explored the adaptability of integrated multi-modal transport systems, a critical gap remains in understanding the impact on transportation accessibility, particularly for transit-reliant communities. This study utilizes spatial indicators to depict accessibility changes at FRT bus stops post-integration with on-demand services. To assess the enhancement in accessibility resulting from integration, the study employed an agent-based model, testing two scenarios: *i) Walking with FRT* and *ii) On-demand Feeder with FRT* (DRT and TNC integrated as feeders). The evaluation employs key metrics, including Transit Coverage Gap, the Lorenz curve, and the Gini index, to analyze the accessibility and equity of the integrated services. Additionally, a novel measure, termed the "Accessibility-Radius," is proposed to quantify spatial accessibility to FRT services. Accessibility-Radius (AR) is defined as the radial service range of a public transit stop, which captures the dependence of the users of the FRT stop to access the public transit facilities. In this study, we quantified the AR as the 90th and 95th percentile distances between various origins and the nearest FRT stops of completed trips. The results of a case study of the city of Morristown, Tennessee, US, indicate that after integration, the Gini index improved from 0.88 to 0.71, and 29.6 % more people had access to public transportation. The study also utilizes the AR performance metric to evaluate a recently developed transit integration project in Memphis, Tennessee, US. The results demonstrate a remarkable 224 % improvement in transit coverage Gap at an FRT stop. Therefore the contribution of this study is a framework to evaluate the accessibility and equity enhancement for a public transit system after integrating with on-demand feeder services.

1. Introduction

In modern societies, public transportation is of utmost importance, as it plays a vital role in promoting sustainable and equitable urban development. Past studies have reported that efficient public transportation can bridge the mobility gap between captive and choice riders, granting access to a variety of social, recreational, educational, and communal facilities, including jobs and healthcare (Guo et al., 2024; Mishra et al., 2015; Sharma et al., 2020; Welch and Mishra, 2013). It is important to note that transit-dependent communities often overlap with economically, physically, and socially disadvantaged populations (Jiao and Dillivan, 2013). Thus, the public transit authorities bear the responsibility of providing equitable transit services to both choice and transit-dependent riders, ensuring comparable levels of service. In the United States, public transportation agencies have the mandate to promote mobility within their designated service areas (Litman, 2022). Moreover, the Title VI of the 1964 Civil Rights Act mandated equity in service, and public transit agencies must consistently conduct equity analyses to ensure compliance (Karner and Levine, 2021). By upholding the principles of equitable transit service, public transit agencies contribute to the promotion of social and economic equity, ultimately fostering sustainable urban development.

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Simultaneously, innovative mobility solutions are broadening transit agencies' potential to enhance their services. These agencies are exploring integration of on-demand mobility services like Demand Response Transit (DRT) and Transportation Network Companies (TNC) into the conventional Fixed Route Transit (FRT) system to enhance accessibility, connectivity, and equity in transportation services (Sultana et al., 2018; Yan et al., 2021; Mishra et al., 2022). The idea of an integrated system originated from the inherent limitations of FRT systems, which include limited spatial access due to fixed routes and fixed schedules, and thus generated a need for improved connectivity and accessibility (Curtis et al., 2019). The integrated public transit systems primarily aims to provide first and last-mile connectivity to existing FRT services, making them more accessible and it is becoming increasingly popular among transit authorities worldwide to solve transportation problems.

In assessing the viability of integrated multi-modal transport systems, it is imperative to explore their adaptability, besides quantifying the associated benefits for effective communication of their efficacy. To ensure the reliability of the integrated systems, stakeholders must conduct thorough pre-installation studies to quantify the improvements in FRT accessibility and explain the proposed system's equity. While existing research has investigated on the adaptability of integration (Leffler et al., 2021; Aravind et al., 2024; Narayan et al., 2020a), a critical gap remains in understanding how this integration influences transportation accessibility and equity, particularly for communities reliant on transit. Notably, there is limited literature providing established measures to quantify accessibility improvements resulting from such integration.

Further, the transportation equity researchers focus their efforts on evaluating the social fairness of transportation systems, specifically examining how the distribution of accessibility provided by these systems impacts various segments of the society (Pereira et al., 2016). Despite the centrality of accessibility as a pivotal measure of spatial and social equity in transportation infrastructure, its measurement is often found to be inadequate. This study addresses this gap by focusing on FRT bus stops, utilizing spatial indicators to depict accessibility changes of FRT, post-integration with on-demand services. In addition, we defined transit coverage gap as the disparity between transit demand and supply, and introduced Accessibility-Radius (AR) as metric to quantify the improvement in transit coverage gap. This measure plays a crucial role in uncovering disparities in transit service distribution, providing crucial insights into potential inequities in transit accessibility. Thus, this paper endeavors to fill the research gap, offering nuanced insights into the quantification of efficiency of service integration and its implications for transportation equity.

The remainder of this paper is structured as follows: In Section 2, a comprehensive literature review on transit coverage, equity, and integrated on-demand public transit systems is examined. This section also highlights the existing research gaps in the field. Section 3 describes the methodology for the transit coverage analysis and the performance measures to quantify accessibility. Section 4 reports the results of the integration and provides a critical discussion of the findings. Finally, in Section 5, the study is summarized with the significance of the findings and the scope for improvement and further research.

2. Literature review

The literature review summarizes a comprehensive examination of studies regarding transit coverage, equity, and integrated on-demand public transit systems. It provides insights into diverse transit coverage matrices and highlights studies that assess the impact of integrated on-demand public transit systems on enhancing accessibility and equity within transit networks. Lastly, the section concludes by providing an overview the research contributions of the study.

2.1. Accessibility, transit coverage, and equity

The literature on accessibility shows that various studies have defined and measured accessibility in a diverse manner, often resulting in misunderstandings of the concept and inadequate measurements (Geurs and Wee, 2004). Various studies have attempted to tackle the issue of accessibility using different methods. For instance, a few studies have referred to accessibility as "potential opportunities for interaction" (Chen et al., 2020; Hansen, 1959)), while others have used the term "ease of reaching activities" (Di Ciommo and Shiftan, 2017). Additionally, some researchers have referred to accessibility as "the proximity of one place to another" (Tsou et al., 2005). Accessibility is also frequently used to describe the results of transportation infrastructure development (Stepniak and Rosik, 2013; Gutiérrez et al., 2011). In particular, in the public transportation research domain, the supply of transit is often seen as synonymous with transit access (Aman and Smith-Colin, 2020). Nevertheless, this study examines accessibility as a metric for accessing FRT stops, which refers to the spatial range within which these stops can be reached. This accessibility is then quantified using the metric Transit Coverage Gap to quantify the access to FRT stops.

Transit coverage: Transit coverage is a level-of-service metric that examines the spatial availability of transit on a large-scale network (Ding et al., 2018; Fayyaz et al., 2017; Whitmore et al., 2022). Coverage measurements are particularly important for identifying latent or unmet transportation demands within a transit system (Assoc, K.&., Brinckerhoff, P., Group, K., Institute, T.A.T., Arup, 2013). The output of a transit coverage analysis is the proportion of a population that a transit system might possibly serve (Jiao and Dillivan, 2013; Fayyaz et al., 2017). Three standard methods for analyzing system-level accessibility coverage are Time of day, the Local Index of Transit Availability (LITA), and the Transit Capacity and Quality of Service Method (TCQSM) (Mamun and Lownes, 2011; Carleton and Porter, 2018a). The Time-of-Day tool analyzes transit demand data to show where demand is unmet, which might lead to frequency or capacity improvements (Polzin et al., 2002; Ibarra-Rojas et al., 2015). The LITA method determines a system's service intensity based on capacity, frequency, and service coverage (Rood and Sprowls, 1998). TCQSM combines temporal and spatial data to determine system coverage (Wei et al., 2018; Ding et al., 2018; Assoc, K.&., Brinckerhoff, P., Group, K., Institute, T.A.T., Arup, 2013).

This study utilizes the TCQSM method for coverage analysis due to its capacity to analyze data at the most granular spatial unit, thereby providing an accurate representation of smaller communities, especially those with low-income or minority populations. Such communities are frequently neglected in large-scale, aggregated geographical analyses (Oudejans, 2017). This process of determining transit coverage involves examining the relationship between transit demand and supply. It relies on comprehending the transit-dependent population and the spatial distribution of transit services. Past research has classified indicators of transit dependence into two primary categories: "income and social class" and "mobility need and ability" (Aman and Smith-Colin, 2020). Analyzing the spatial supply of transit involves recognizing the distances individuals walk to bus stops, and it can vary based on factors like population group, urban spatial conditions, and the type of transit stop (Currie, 2010; Garcia-Palomares et al., 2018). The walking region surrounding a bus stop, often referred to as the walking buffer zone, is commonly defined with a 400-m radius around a transit stop, considering it a practical walking range of a trip-maker for accessing transit services (Garcia-Palomares et al., 2018; Mulley et al., 2018). Despite the existence of various methods for assessing transit service levels, a standardized criterion for transit coverage remains elusive. Transit coverage scores, however, offer valuable insights into areas where transit supply falls short of demand, signaling the need for attention and improvement. Consequently, transit coverage analysis has become a widely adopted method to evaluate equity, highlighting the spatial disparity between transportation supply and demand.

Transit Equity: It can be misleading when "equity" is used interchangeably with other terms such as equality (Carleton and Porter, 2018b), fairness, and justice (Manaugh and El-Geneidy, 2012). Although they convey the same idea in general, there are subtle differences between them. For instance, equity involves a "subjective" distribution of resources based on "moral judgment" informed by recipient needs, whereas equality implies a uniform allocation of resources regardless of individual needs, which can be impractical (Carleton and Porter, 2018b). Social equity pertains to the fairness in distributing the expenses and benefits of a resource, among a group of people (Pereira et al., 2016; Litman, 2017), and similarly, transit equity refers to how public transportation providers share their services among diverse communities (Jiao and Dillivan, 2013; Wei et al., 2018). Equity analysis aims to determine whether transportation services are provided in a non-discriminatory manner.

Inequity in public transportation has been shown in the literature using the Lorenz curve and the Gini Index. Lorenz curves, for instance, were utilized by Delbosc and Currie (2011) and Ricciardi et al. (2015) to assess the degree of overall transport equity experienced by a group in terms of employment and population. Quantitative studies have also analyzed transit equity via transit coverage (e,g., Litman (2022); Mamun and Lownes (2011)), and the costs of achieving social justice from both the agency and rider perspectives (e,g., Wei et al. (2018); Garrett and Taylor (2012); Feitelson (2002); Carleton and Porter (2018a). Several studies (e,g., Wei et al. (2018); Fagnant and Kockelman (2018)) have quantitatively investigated the effects of changes to transit services on the mobility of the transit-dependent population. Given evolving transportation technologies, there is a crucial need for equity examinations, necessitating further research to quantify their benefits. As transit systems increasingly adopt advanced mobility solutions like integrated public transit systems, it becomes imperative to quantify their social impact and accessibility to ensure equitable transportation.

2.2. Integrated on-demand public transit system

Existing mobility options have been made substantially simpler by new technologies (Shaheen and Chan, 2016). Connecting customers with on-demand transit as a feeder to the FRT to form an integrated transit system has the potential to encourage the usage of public transit (Shaheen and Chan, 2016; Shaheen and Cohen, 2020). Several notable research works have been conducted in this field, including studies by Aldaihani et al. (2004); Wen et al. (2018); Stiglic et al. (2018); Narayan et al. (2020b); Mishra et al. (2022); Aravind et al. (2023). Studies have shown that integrated transit facilities can improve transit coverage and encourage a modal shift from privately owned automobiles to more sustainable modes by offering first and last mile connectivity. (Auad-Perez and Hentenryck, 2022; Stiglic et al., 2018). Moreover, research conducted in São Paulo highlights the capacity of DRT services to complement existing bus routes, attracting passengers from private transportation modes by providing comparable service quality at competitive fares (Costa et al., 2021).

Methodologically, Wen et al. (2018) employed an ABM simulation to assess the efficacy of an integrated demand-supply framework utilizing autonomous vehicles as FRT feeders. In contrast, Calabrò et al. (2023) leveraged continuous approximation to model the dynamic responsiveness of adaptive transit systems to real-time demand fluctuations, thereby optimizing accessibility and cost-efficiency. Hasif et al. (2022) adopted a graph-database approach to evaluate the impact of DRT services on public transit accessibility, providing insights into network connectivity and user satisfaction. These studies have demonstrated the capability of these integration models to enhance transit system efficiency, reduce travel times, and optimize vehicle utilization, particularly in low-density suburban areas.

Despite the advantages it offers, on-demand mobility also has certain drawbacks. While on-demand transportation can be really helpful for some people, we need to make sure it's helping everyone. Understanding the impact of these new mobility solutions on transit-dependent individuals is essential. This raises concerns about fairness and inclusivity, making the evaluation of shared mobility's impact on transportation equity vital for urban planners and policymakers (Shaheen and Chan, 2016; Kortum et al., 2016; Shaheen et al., 2019). Similarly, equity-related laws like Title VI and the Americans with Disabilities Act have been enforced inconsistently by ride-hailing companies Denney (2018). Examining the equity distribution of an integrated system is crucial to establish its applicability among transit-dependent social groups. However, there is minimal empirical research on how these emerging modes of mobility improve transit access and assist transit-dependent riders.

2.3. Research contribution

In the light of above mentioned challenges, our analysis focuses on determining whether integrating on-demand services into existing FRT systems can effectively bridge the gap between transportation demand and supply of the area. To achieve this, the paper focus on two case studies: the transit systems in the cities of Morristown and Memphis in Tennessee, USA. The aim of this paper is two fold: (i) evaluation of existing public transport accessibility and examination of transit coverage gap to identify priority service areas with unmet transit needs and equity challenges based on socio-demographic variables; and (ii) propose a novel measure of Accessibility-Radius to quantify and evaluates the equity and accessibility of a transit system where FRT is integrated with of on-demand services as feeders. The research's analytical findings give evidence to planners to play a more active role in exploring these innovative mobility options to enhance transit networks.

3. Methodology

The analysis comprises three pivotal steps. Firstly, it involves the estimation of the existing transit coverage gap of the area based on the transit demand of the study area and transit supply provided by the FRT network. The second step involves the integration of on-demand services as feeder services to the FRT using agent-based simulation. Finally, the third step focuses on implementing performance measures to assess the increased Accessibility-Radius and the consequent enhancement in transit coverage gap resulting from the integration of on-demand feeder services with the FRT network.

3.1. Transit coverage analysis

To successfully identify the locations in the study area with unmet transit demands, a transit coverage gap score must be determined. As explained in the literature review, the score for transit coverage gap is a metric that is included in the TCQSM (Assoc, K.&., Brinckerhoff, P., Group, K., Institute, T.A.T., Arup, 2013). It is formulated as a function of both transit supply and transit demand, providing insight into how well the existing transit supply caters to the transit demand within the area.

3.1.1. Estimation of transit demand

The transit demand was assessed as a function of the total number of transit-reliant residents in the study area. In this study, six specific variables were considered to identify the population that depends on public transportation within each spatial unit (SU) which belongs to two main categories: "income and social class" and the "mobility need and ability". The initial set of indicators encompassed household income, education level, automobile ownership, and the census data of workers who use public transit as means to commute, all falling within the domain of "income and social class". Additionally, the "mobility need and ability" category encompasses the age groups of seniors aged 65 and above, as well as minors aged 10 to 17. Table 1, shows the indicators and the thresholds of the indicators used in the study. The population data for each indicator in each SU was obtained from the United States

Table 1
Transit demand indicators.

Indicator	Criteria	References
Education	Individuals older than 25 years and education less than 9th grade	Currie (2010); Manaugh and El-Geneidy (2012)
Automobile Ownership	No automobile to their name	Aman and Smith-Colin (2020)
Transit Users	Individuals who use transit for work	Manaugh and El-Geneidy (2012); Aman and Smith-Colin (2020)
Age (Elder)	Older than 65	Mamun and Lownes (2011)
Age (Youth)	10 to 17	Manaugh and El-Geneidy (2012)
Income	Less than $14,999	Adli et al. (2019); Healthcare.gov (2024)

Census Bureau (Bureau, 2011). Since all the indicators were assumed to carry equal weight, the transit-dependent population density per SU ($\mathscr{D}_{SU_i}$) was determined through direct summation of these indicators. The scores were computed by summing the proportional value of each indicator relative to the total population of the SU as shown as in Eq. (1).

$$\mathscr{D}_{SU_i} = \frac{1}{P^{total}_{SU_i}}\left[P^{edu}_{SU_i} + P^{elder}_{SU_i} + P^{youth}_{SU_i} + P^{tu}_{SU_i} + P^{inc}_{SU_i} + P^{ao}_{SU_i}\right] \tag{1}$$

Where, $P^{total}_{SU_i}$ is total population of the spatial unit. These indicators include $P^{edu}_{SU_i}$ represents the population aged 25 years and older with less than a 9th-grade education level. $P^{elder}_{SU_i}$ denotes the elderly population aged 65 years and older. The youth population aged 10 to 17 years is represented by $P^{youth}_{SU_i}$. The term $P^{tu}_{SU_i}$ reflects the number of individuals who use transit for work-related travel within the spatial unit. $P^{inc}_{SU_i}$ identifies the population with an annual income of less than $14,999. Finally, $P^{ao}_{SU_i}$ accounts for the population of individuals who do not own a personal automobile.

The Demand score values were then normalized as per Eq. (2) to get the normalized transit demand $\left(\mathscr{D}^{norm}_{SU_i}\right)$ to ensure a direct comparison between the transit demand and the transit supply calculated in the next stage.

$$\mathscr{D}^{norm}_{SU_i} = \frac{\mathscr{D}_{SU_i} - \mathscr{D}^{min}_{SU_i}}{\mathscr{D}^{max}_{SU_i} - \mathscr{D}^{min}_{SU_i}} \tag{2}$$

Where $\mathscr{D}^{norm}_{SU_i}$ is the normalized value of transit demand, $\mathscr{D}_{SU_i}$ is the original value we want to normalize. While $\mathscr{D}^{min}_{SU_i}$ represents the minimum value in the range of transit demand values within the whole study area, and $\mathscr{D}^{max}_{SU_i}$ is the maximum value of the range. For the calculated scores, the quartiles were estimated, to find the SUs with different levels of transport dependency (Aman and Smith-Colin, 2020). Additionally, it is assumed that demand within each spatial unit is uniformly distributed across the entire area.

3.1.2. Estimation of transit supply

In the context of a well-connected public transit system, it is essential that the routes and transit stops are situated in close proximity to individuals who rely on public transit. This aspect of accessibility not only minimizes travel time but also encourages the usage of public transportation. To assess transit supply, the TCQSM (Assoc, K.&., Brinckerhoff, P., Group, K., Institute, T.A.T., Arup, 2013) incorporates a service coverage metric, which necessitates the availability of transit stops. In this study, we employ the transit stop service coverage area ratio as the transit supply indicator. We assumed a walking buffer zone of 400-m (0.25 miles) radius centered on a transit stop to assess the spatial coverage of that transit stop. Each spatial unit was then assigned a supply index (SI) that gives the spatial access coverage as per Eq. (3) (Assoc, K.&., Brinckerhoff, P., Group, K., Institute, T.A.T., Arup, 2013).

$$\mathscr{S}_{SU_i} = \sum_{n}^{N}\left(\frac{\mathscr{A}_{B_n}}{\mathscr{A}_{SU_i}}\right) \tag{3}$$

Where $\mathscr{S}_{SU_i}$ represents the supply score for the investigated spatial unit SU_i, N is the total number of walk access buffers to transit stops in each spatial unit, and $\mathscr{A}_{B_n}$ is the area of the buffer B_n for each stop in each spatial unit. $\mathscr{A}_{SU_i}$ is the total area of each spatial unit. The transit supply was then normalized as per Eq. (4) $\left(\mathscr{S}^{norm}_{SU_i}\right)$ and made compatible with the transit demand values.

$$\mathscr{S}^{norm}_{SU_i} = \frac{\mathscr{S}_{SU_i} - \mathscr{S}^{min}_{SU_i}}{\mathscr{S}^{max}_{SU_i} - \mathscr{S}^{min}_{SU_i}} \tag{4}$$

Where $\mathscr{S}^{norm}_{SU_i}$ is the normalized value of transit supply, $\mathscr{S}_{SU_i}$ is the original transit supply value we want to normalize. While $\mathscr{S}^{min}_{SU_i}$ represents the minimum value in the range of transit supply values, and $\mathscr{S}^{max}_{SU_i}$ is the maximum value of the range.

3.1.3. Estimation of transit coverage gap

The transit coverage gap scores ($\mathscr{T}_{SU_i}$) scores for each spatial unit SU_i were derived by evaluating the difference between its normalized transit supply ($\mathscr{S}_{SU_i}$) and the corresponding normalized transit demand $\left(\mathscr{D}^{norm}_{SU_i}\right)$ as per the Eq. (5) (Whitmore et al., 2022).

$$\mathscr{T}_{SU_i} = \mathscr{S}^{norm}_{SU_i} - \mathscr{D}^{norm}_{SU_i} \tag{5}$$

The determination of transit coverage gap scores through demand and supply analysis aids in the identification of areas characterized by high demand and limited service, referred to as transit gaps. These are regions where high transit dependence and low transit supply overlap. A negative transit coverage gap score signifies the presence of a transit gap or a need, indicating that the demand for transit exceeds the available supply. Conversely, a positive value indicates that there is an adequate or surplus supply of transit to meet the needs of the population. The attainment of an optimal equilibrium between demand and supply is achieved when the coverage value reaches zero. Therefore, the transit coverage gap values range from [−1,1] and are appropriately expressed as percentages within the range [−100,100].

3.2. On-demand feeder integration to FRT

The concept of integrated public transit scenarios refers to situations where an individual utilizes multiple modes of public transportation to travel from one destination to another. In our study, we employed the methodology used in Aravind et al. (2023), where an agent based simulation framework was used for creating multiple scenarios integrating on-demand services such as DRT and TNC as feeder modes to complement the existing FRT network. There are two main scenarios in our study, depending on the type of service employed during the journey: (i) *Walking with FRT* and (ii) *On-demand Feeder with FRT*. The second scenario can further be divided into sub-scenarios based on the number of transit legs involved in a trip and the chosen mode of transportation for each leg.

For the simulation, trip makers are modeled as agents within the model were assigned specific personal traits, and each scenario was evaluated for every possible origin-destination pair. The model assumes a fleet comprising vehicles of the same type, with uniform attributes such as capacity, speed, and route choice. Each mode of transportation is characterized by a constant speed, which is presumed to be maintained throughout the entire journey. The basic structure of the proposed ABM simulation framework consists of three essential components: the agent, the transport modes, and the transport networks. The agent (i) draws requests from the OD matrix and is characterized by various factors, and intent to complete their trip between a pair of origin (o) and destination

(d), with minimal generalized user cost $f(c)^{od}_{user,i}$ for every scenario (j). The network data comprises of the local road network and the FRT network, represented by a set of nodes and the connecting links. The DRT and TNC modes considered in the study utilize the local road network and the FRTs use only the dedicated FRT routes with predefined stops, which is a subset of the local network. The study also assumes that public transit agencies directly operate FRT and DRT, and DRT is considered as a transit mode. Table 2 shows the average speed values used in the model.

3.2.1. Scenarios

Scenario-1: *Walking with FRT:* This scenario is only possible if the FRT stops fall within the walking buffer of both the origin and destination. In such cases, the individual making the trip can walk to and from the nearest FRT stop to their origin and destination. It is crucial to note that this scenario does not incorporate any integration with on-demand mobility services and instead relies exclusively on the existing FRT service available in the area. Therefore, it is not feasible to complete every trip using this method.

Scenario-2: *On-demand Feeder with FRT:* If either or both the origin and destination are outside of the walking buffer of the nearest FRT stop, the completion of a trip involving FRT requires the use of feeder services to provide connectivity at the first mile, last mile, or both. This situation gives rise to integrated scenarios that can have two or three legs, depending on the locations of the origin and destination.

For every O—D pair, a trip comprises of the trip-maker searching for FRT stops and waiting for the next service. This service can either be an on-demand service (DRT or TNC), which acts as a feeder to or from the nearest FRT stop, or it can be the upcoming FRT service itself. Based on the services chosen in different legs of the trip, Scenario 2 can be made into four sub scenarios: $S_{TNC-FRT}$, $S_{DRT-FRT}$, $S_{TNC-FRT-DRT}$, and $S_{DRT-FRT-TNC}$. In the $S_{TNC-FRT}$ and $S_{DRT-FRT}$ scenarios, a single type of on-demand service that is either a TNC or DRT, respectively, is used as a feeder, providing first-mile or last-mile, or both connectivity. Whereas, $S_{TNC-FRT-DRT}$, and $S_{DRT-FRT-TNC}$ uses two types of services as feeders in the first mile and last mile of the trip. Fig. 1 represents the schematic diagram of all the possible scenarios.

3.2.2. Generalized user cost

For each origin-destination (OD) pair and under various scenarios and sub-scenarios, a comprehensive measure of generalized user cost is computed. This measure encompasses both time and monetary aspects. It takes into account in-vehicle travel time, as well as out-of-vehicle times such as waiting time. These time components are assigned a cost based on a designated Value Of Time (VOT). VOT represents the implicit opportunity cost associated with the time a traveler spends in transit, reflecting the amount of money an individual is willing to pay to reduce travel time. This concept quantifies time in monetary terms, allowing it to be integrated into financial calculations and decision-making processes.

VOT is typically variable and is influenced by both the traveler's income level and the purpose of the trip. Generally, individuals with higher incomes exhibit higher VOTs, as they are more inclined to pay a premium to save time, thereby reflecting the greater opportunity cost of their time. This relationship arises because VOT estimates are fundamentally grounded in willingness-to-pay principles, whereby those with higher incomes assign a greater monetary value to their time compared to individuals with lower incomes (Kockelman et al., 2013; Fournier and Christofa, 2020; Ye et al., 2009). By converting transit time into its equivalent monetary value using the VOT, the final generalized user cost values are determined in US dollars, following Eq. (6).

$$f(c)^{od}_{user,i} = \sum_{m}^{M}\left[\lambda_{od}\times\left(t^{iv}_{i,m}+t^{ov}_{i,m}\right)\right]+\gamma_{i,m}\times d_{i,m} \quad (6)$$

where,

$$t^{iv}_{i,m} = d_{i,m}\Big/\nu_{i,m} \quad (7)$$

$$t^{ov}_{i,m} = \delta 1_{i,m}\times t^{wt}_{i,m} \quad (8)$$

Where M is the set of available travel modes, and walking in a case of finding walking time to FRT stops (TNC, DRT, FRT, walk), $t^{iv}_{i,m}$ is the in-vehicle travel time for mode m in scenario i, $t^{iv}_{o,m}$ is the out-of-vehicle travel time for mode *m* in scenario *i*. $\lambda_{od,m}$ is the value of time for mode *m*, $\gamma_{i,m}$ is the distance based fare for mode *m* in scenario *i*. $d_{i,m}$ is the trip distance for mode *m* in scenario *i* ($d_{i,m}$ =1 if flat fare), $\nu_{i,m}$ is the average travel speed for mode *m* in scenario *i*. $t^{wt}_{j,m}$ is the waiting time for mode *m* in scenario *i* or the walking time to FRT stops. The values of $\delta 1_{i,m}$, are 1 if the respective waiting time is applicable for mode *m* in scenario *i*, else zero. Moreover, it was assumed that the VOT for trips originating from each spatial unit reflects the income level of the population residing in those zones (Kockelman et al., 2013; Fournier and Christofa, 2020; Mishra et al., 2022; TRR, 1977).

After selecting a set of OD pairs, a generalized user cost is calculated for each alternative. Within the scope of this study, the completion or failure of demanded trips is assumed to be dependent on a predefined price cutoff for the generalized user cost. Trips with excessively high costs may be deemed not affordable and, consequently, considered inaccessible to individuals, and hence not completed.

3.3. Performance measures

The study employed two distinct measures to determine the effectiveness of integration. The initial method involves the calculation of an enhanced Accessibility-Radius to determine the expanded transit coverage gap of an FRT stop after the integration. The second method entails the application of the Lorenz curve and Gini Index to evaluate the improvement in equity of the service resulting from the integration.

3.3.1. Increased accessibility-radius

The Accessibility-Radius, is defined to estimate the improvement in transit coverage gap of an FRT stop after integration. The concept of AR corresponds to the radial range within which a public transit stop provides service. This measure quantifies the extent to which users of the FRT system count on the accessibility of public transit facilities. With this radius we define a buffer region around the FRT stop called FRT accessibility-buffer. Calculation of the AR for each successful trip involves determining the Euclidean distance between its origin point and the nearest FRT stop. To establish the buffer region, the 85th, 90th, 95th, or 98th percentile values of the distance between the origin and the FRT stop are utilized. This FRT accessibility-buffer represents the area within which origins can access the FRT stop using feeder services, thus expanding the overall accessibility of that particular transit stop.

The expansion of the FRT accessibility-buffer zone allows for greater accessibility to the transit stop for trip-makers located beyond the feasible walking distance. Since we consider that public transit agencies directly operate FRT and DRT, there will be an increased supply of transit with the accessibility buffer. To ensure that the trips remain affordable for all individuals, a price cutoff is applied. This criterion ensures that the cost of the trips falls within an acceptable range for the general population. With the new radii derived from the percentile values, the spatial coverage transit supply values are recalculated using Eq. (1). These updated values reflect the extended reach of the transit

Table 2
Average speed for model application.

Values Considered	FRT	DRT	TNC
Average speed (miles/H)	12 (Hughes-Cromwick, 2019)	15.2 (Hughes-Cromwick, 2019)	20 (Tarduno, 2021)

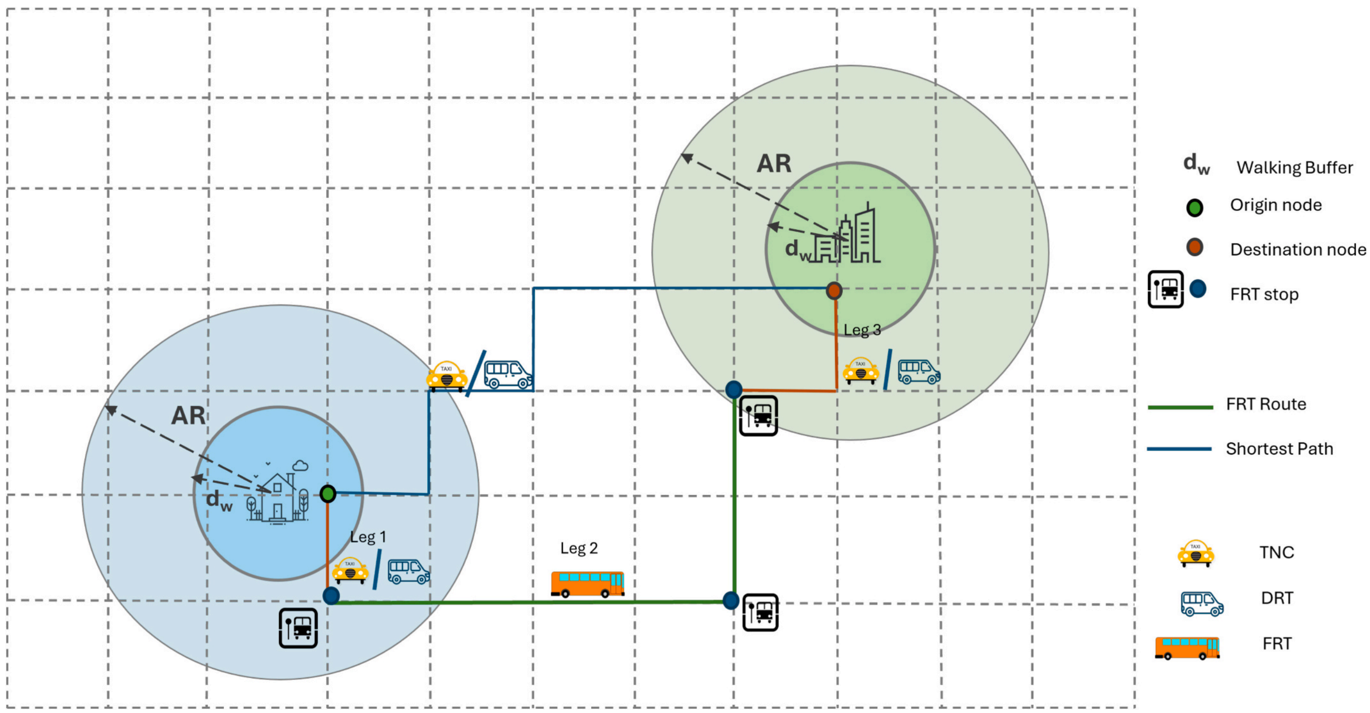


Fig. 1. Schematic Representation of On-demand Feeder Integration.

system. The transit coverage gap for each spatial unit is then determined by considering both the increased transit supply and the existing travel demand of that specific spatial unit. This assessment provides an evaluation of the accessibility and availability of transit services within each spatial unit.

3.3.2. Equity and Gini index

The Lorenz curves and Gini index are common non-modeling techniques for measuring equity (Welch and Mishra, 2013; Delbosc and Currie, 2011; Kaplan et al., 2014). In the field of economics, Lorenz curves provide a graphical representation of the cumulative distribution of wealth or any other variable across a population, originally introduced by Lorenz (1905). These curves can be applied to various variables that can be accumulated throughout a population. While the Lorenz Curve is a visual depiction, the Gini index is a single basic mathematical metric that represents the overall degree of inequality (Delbosc and Currie, 2011). A larger deviation of the Lorenz curve from the line of equity indicates a less equitable scenario. The Gini index, on the other hand, serves as a measure of the extent to which a distribution deviates from perfect equity. A Gini index value of zero represents perfect equity, while a value of one denotes perfect inequity (Bureau, 2011). In this study, the generalized user cost for various scenarios is employed to assess the Gini Index across various scenarios, serving as a financial performance indicator for the integrated system.

4. Results and discussion

4.1. Case study: City of Morristown

The first study area is the city of Morristown in the county of Hamblen, Tennessee, US. Morristown has an existing DRT service and newly started FRT service with three separate routes and 29 FRT stops. Morristown has an existing DRT service and a newly started FRT service with three separate routes and 29 FRT stops. Data from DRT daily travel tickets were utilized for our analysis, and the Transit Agency was cooperative in providing this information. As Morristown is a small city with plans to expand its FRT coverage by integrating DRT services in the future, it serves as an ideal study area. The origin and destination of trips were geocoded using coordinates from the ticket data. Additionally, in our analysis, the DRT service was booked through a transit app, functioning similarly to a TNC service. This study employs information from three distinct sources:

i. General Transit Feed Specification (GTFS) information on transit network features

ii. Existing DRT trip data and attributes

iii. The socioeconomic data and road network of Tennessee

The overall data consists of 381 distinct O—D combinations with varied demand, and a total of 27,906 trips. The spatial unit considered for the case study is census tracts and the study included 29 census tracts with a combined population of 104,504. Fig. 2 depicts the geographic representation of Morristown, with the trip origin points, and the existing FRT stops and routes.

4.1.1. Transit coverage gap of existing FRT system

The existing FRT system served only three routes and was located in the central part of the study area. The transit demand was assessed by calculating a standardized transit demand value that takes demographic factors into consideration. Fig. 3a depicts the distribution of census tracts' potential transit demand in the categories of Low, Low-Moderate, Moderate High, and High values, i.e., the higher the score, the greater the potential demand for public transportation. The spatial distribution of demand was high or moderately high in 14 census tracts in the city's core and west side. The demographic characteristics in those census tracts include 35 % of the population below the poverty line, 43 % of the population in transit-dependent age including children and elderly, 18.5 % of the population without a high school degree, and 34.6 % of the population with no vehicle ownership. People living below the poverty line, lack of vehicle ownership, and a transit-dependent age population all contribute to the high demand for transit in these census tracts.

Fig. 3b depicts the results of the supply index analysis, with the supply scores in the study area classified as Low, Low-Moderate, Moderate High, and High transit supply. Only 8 census tracts in the study area were served by existing FRT services. More than 72.9 % of the total population in Morristown had no access to public transit, the existing

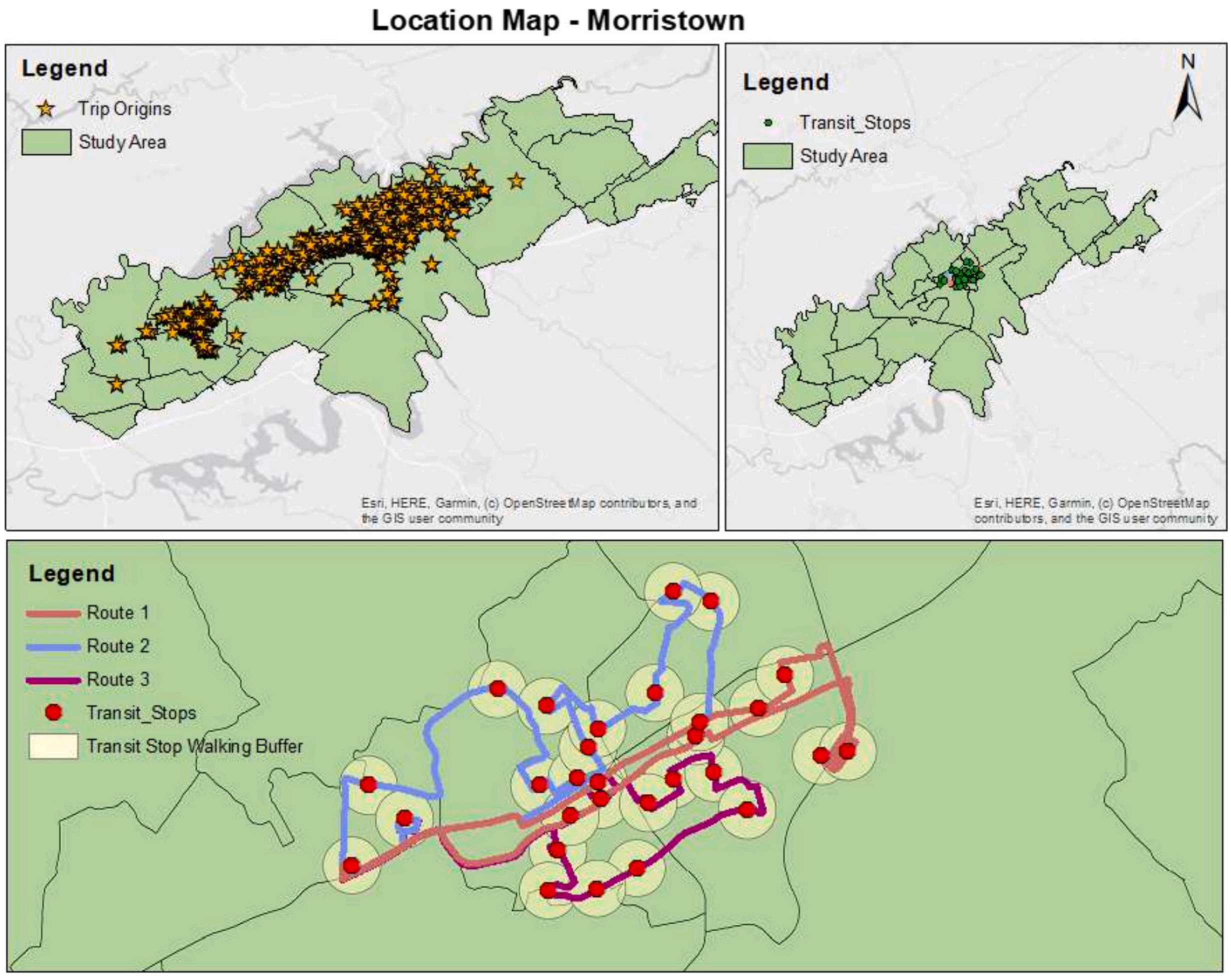
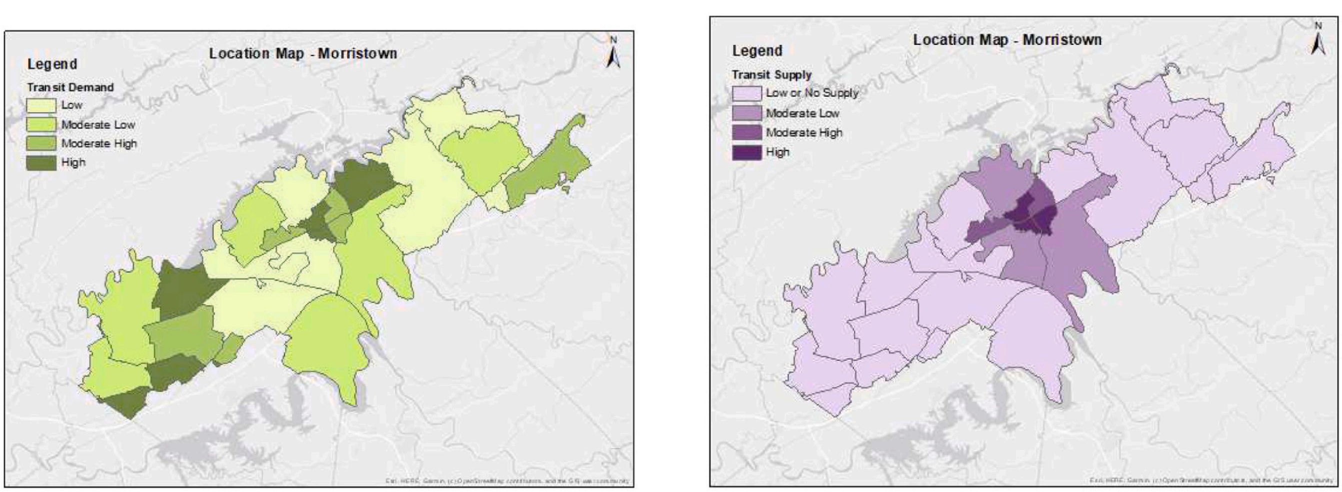


Fig. 2. Study Area: Existing FRT Network and DRT Trips.



(a) Transit Demand

(b) Transit Supply

Fig. 3. Transit Demand and Supply before Integration.

transit supply leaves out 49.6 % of the population below the poverty line. It indicates that about three-quarters of the people in the research area are likely to suffer from inadequate public transit service.

From this transit demand and transit supply, transit coverage gap scores were calculated. Fig. 4 depicts the transit coverage gap map with the existing conditions, without the on-demand feeder integration to FRT. When transit demand exceeds transit supply, a negative transit coverage gap is shown, indicating a transit need or gap. The spatial

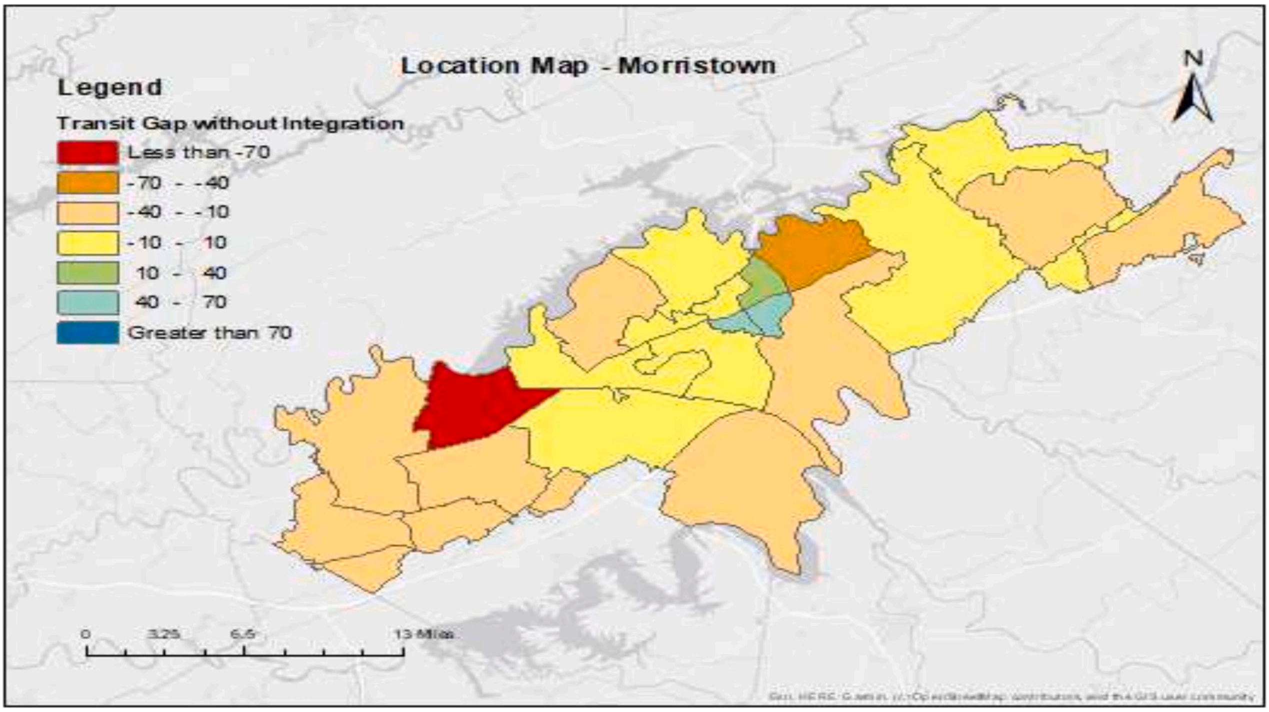


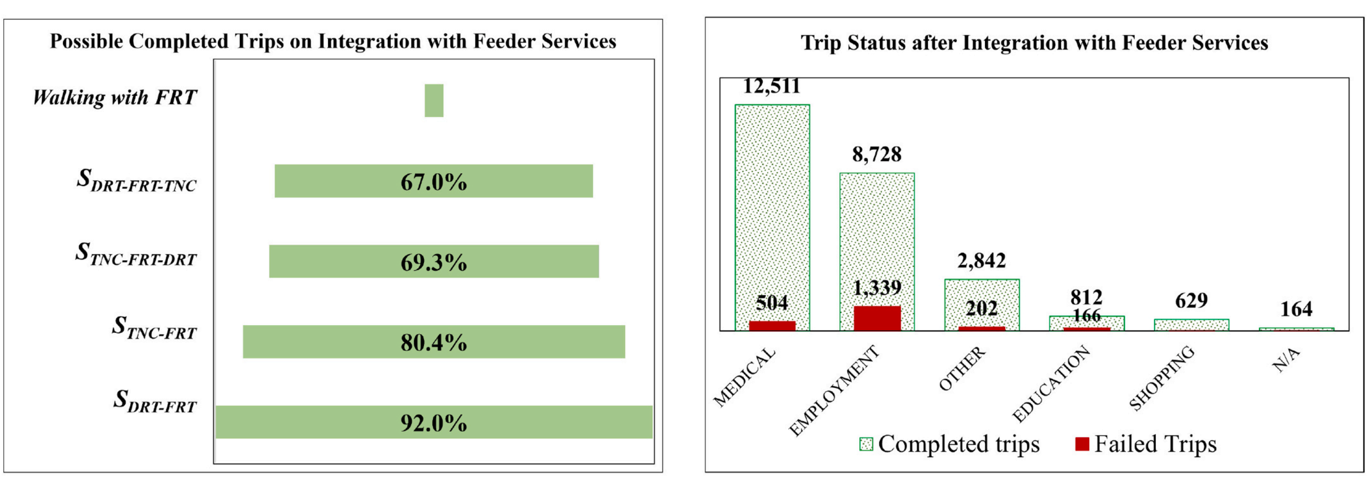
Fig. 4. Transit Coverage Gap (Percentage) without On-demand Feeder Integration.

distribution of transit gaps in Morristown with the existing FRT system reveals that there were coverage gaps everywhere except in the city's core, where transit routes are available. Only five census tracts had a positive transit coverage gap score in which the supply exceeds the demand. The majority of the visible land area had negative transit coverage gap scores, indicating that the supply was not meeting the demand.

4.1.2. *On-demand feeder integration to FRT*

The whole routable local road network of the study area was used to build the network graphs for the on-demand to be integrated with FRT in the service area. The generalized user costs for every trip were estimated considering the value of time, information on FRT, and DRT fares, and schedules obtained from transit agencies. A comprehensive evaluation was conducted on the dataset of 27,906 trips. The evaluation focused on two distinct scenarios and four sub-scenarios of integration, assuming that each trip's origin is connected to its destination through at least one FRT leg. As already described, a price cut-off of $40 for the generalized user cost was set to determine the trips that can be completed in terms of affordability. Any trips beyond this cost were expected to be rejected. This threshold was chosen not only to reflect direct costs, such as ticket fares but also to account for the VOT. The average VOT, taken from the literature (Fournier and Christofa, 2020), indicated an average VOT of approximately $40.32 per hour, based on a household travel survey of 14,159 trips. Furthermore, individuals are generally willing to pay between $1.50 and $3.00 per trip fare for improved transit services (Chung and Chiou, 2017). Considering these values, we select $40 as a reasonable benchmark for the analysis.

Post-simulation results as shown in Fig. 5a indicate that a total of 96.06 % of the simulated trips were successfully completed, out of which 4.02 % of trips were completed through scenario-1 (*Walking with FRT*), and 92.04 % with Scenario-2 (*On-demand Feeder with FRT*) where the



(a) Percentage of Trips Completed using Multiple Scenarios (b) Trip Status after Integration according to Purpose of Trips

Fig. 5. Analysis of Feeder Integration- Morristown.

feeder service provided the first or last-mile connectivity or both. It is to be noted that there is an increase in 88.02 % of more trips completed upon connecting the FRT Service with feeder service. In addition, upon disaggregating scenario-2 into the sub-scenarios, 80.4 % of journeys are possible with $S_{TNC-FRT}$ and 92.04 % with $S_{DRT-FRT}$, while the three modal scenarios can complete 67.4 % of trips through $S_{DRT-FRT-TNC}$ and 69.3 % through $S_{TNC-FRT-DRT}$. Fig. 5b shows the number of completed trips and failed trips as per the trip purpose, with a total of 7.9 % of failed trips. Fig. 6 displays the results of the simulation's breakdown of the number of completed trips by day of the week and time of day.

From the study results, it was found that 92.04 % of the trips were successfully completed with the Scenario-2 with integration of feeder services to the FRT, compared to 4.02 % by the existing *Walking with FRT* system alone. With the increase in trips made possible, there is an increase in accessibility through the new transit supply.

4.1.3. Accessibility-buffer

We measured the Euclidean distance after integration from the origin of completed trips to the nearest FRT stop. The results were 2.54 Km, 4.85 Km, and 7.31 Km, which represented the 85th, 90th, and 95th percentiles of the calculated distances, respectively. The buffer regions with these distances as radii from the FRT stop are shown in Fig. 7. For each transit stop, a new buffer zone has been established, within which it is feasible to use on-demand services as feeders to provide first-and last-mile connectivity. The 90th percentile distance of 4.85 Km was taken for further calculations in the study. With the new feeder buffer, the transit coverage gap scores have been recalculated and are depicted in Fig. 8*a*. Eleven census tracts now have positive transit coverage gap compared to the five census tracts previously. This improved supply currently serves a population of 45.2 %, including 35.54 % of those living below the poverty line, 20.6 % of those without a high school degree, and 44.1 % of the population in transit-dependent age (children and elderly). Increasing the radius from 400 m in *Walking with FRT* scenario to 4.85 Km in *On-demand Feeder with FRT* scenario increased the spatial area coverage by 17.8 times. In addition, it should be highlighted that, with integration, 45.2 % of the total population had adequate access to public transportation, whereas, without integration, only 15.6 % of the population had transit supply (Fig. 8*b*). Therefore, with feeder integration, the transport supply becomes more accessible to an additional 29.6 % of the population.

4.1.4. Gini index

Further, the equity assessment was performed using the Lorenz curve and the corresponding Gini index. Fig. 9a illustrates the Lorenz curve for the transit supply before and after the integration with Feeder services. With the existing FRT service (*Walking with FRT*), the transit supply of the study area has a Gini Index of 0.88, indicating extreme inequity because the services are not available to a large portion of the population. However, after the integration of feeder services to FRT, the Gini index improved to 0.71, indicating a significant improvement in transit service supply.

Fig. 9a also demonstrates that when FRT services were not connected with feeder services, only 20 % of the transit service was utilized by 90 % of the census tract's population. In the meantime, when FRT services were connected with feeders, 90 % of the population shared about 60 % of the provided transit supply. Fig. 9b illustrates the Gini indices for the various scenarios, the curve represents the cumulative share of trip-makers using the service in each scenario and the cumulative share of generalized user cost. The Lorenz curve method, when combined with Gini index, facilitates the comparison of equality between groups. The Gini Index of the $S_{DRT-FRT}$ is 0.16, $S_{DRT-FRT-TNC}$ is 0.39, $S_{TNC-FRT}$ is 0.24, $S_{TNC-FRT-DRT}$ is 0.36 and for the *Walking with FRT* scenario, it is 0.96. Lower Gini Index (e.g., $S_{DRT-FRT}$): Indicates that the Lorenz curve is closer to the diagonal, meaning that user costs are distributed more evenly across users. This suggests a fair and equitable system where most users bear similar costs. Higher Gini Index (*Walking with FRT*): Reflects that a small group of users bears significantly higher costs. This scenario is less equitable, as the costs are unevenly distributed, with considerable disparity among users.

Without integration, *Walking with FRT*, only limited OD was made successful (4.02 %) and hence the least accessible scenario in terms of equity and Gini Index. All of the integrated scenarios are more equitable than the existing FRT network and can be recommended for potential implementation.

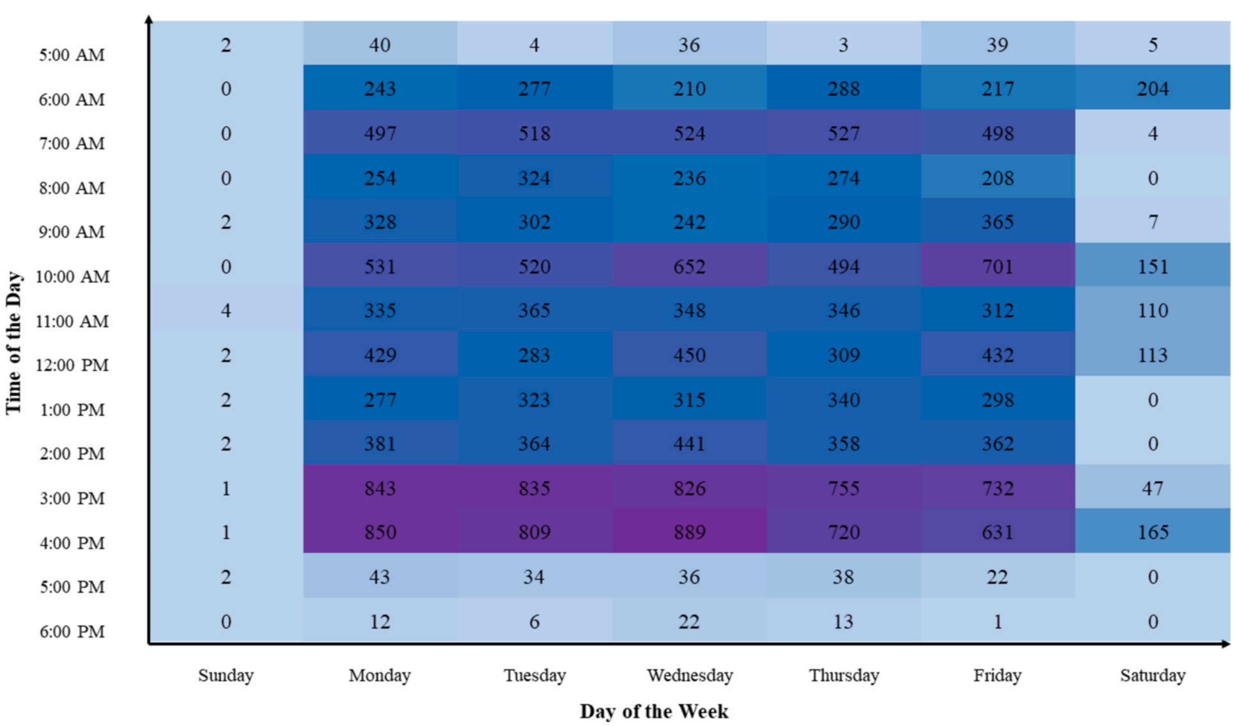


Fig. 6. Completed Trip Distribution-Morristown.

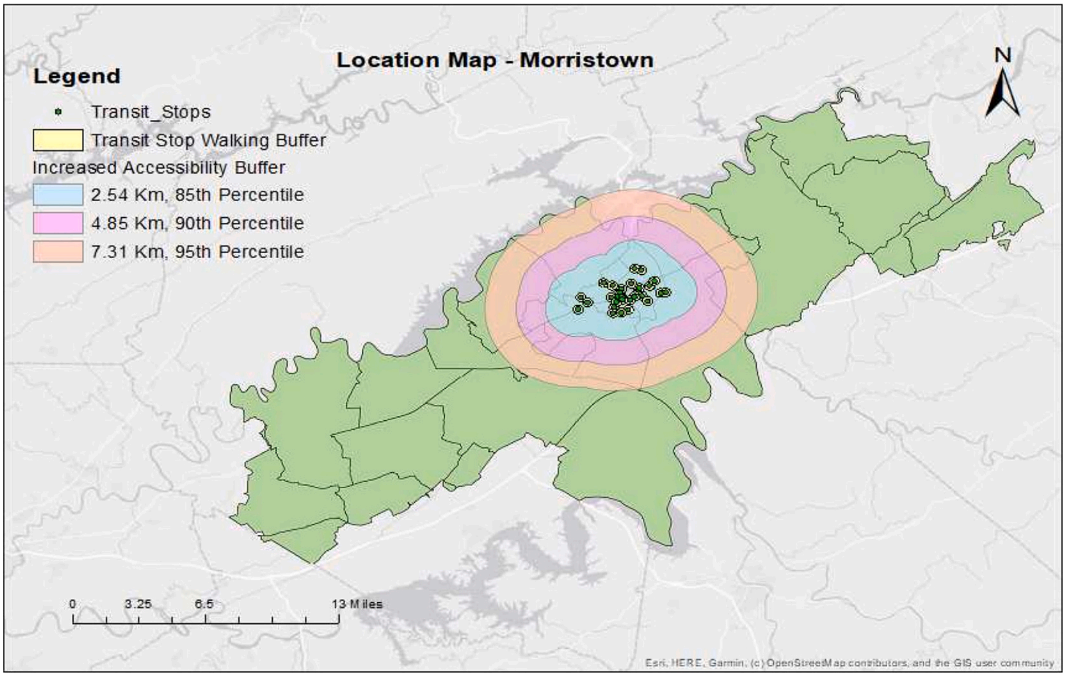
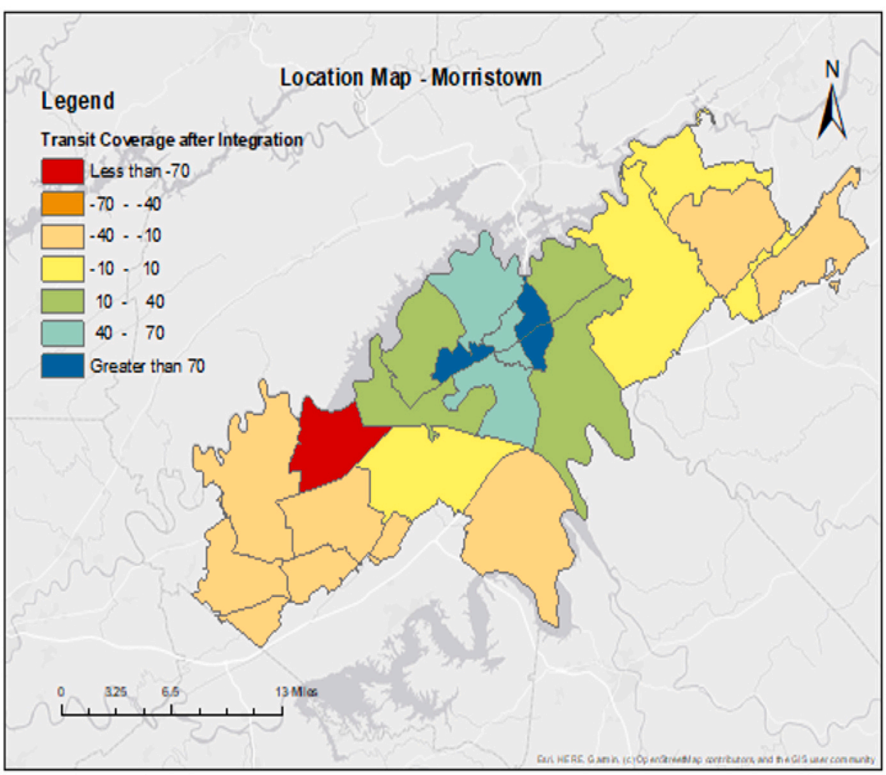
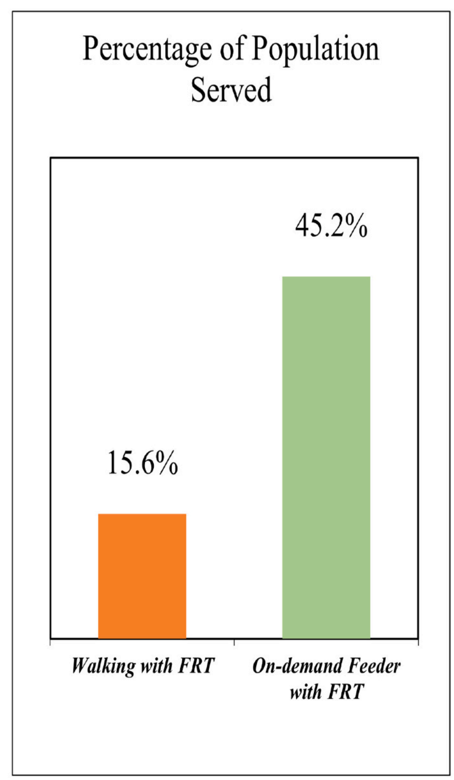


Fig. 7. Increased Accessibility-Buffer: Morristown.



(a) Transit coverage Gap (Percentage) with On-demand Feeder Integration

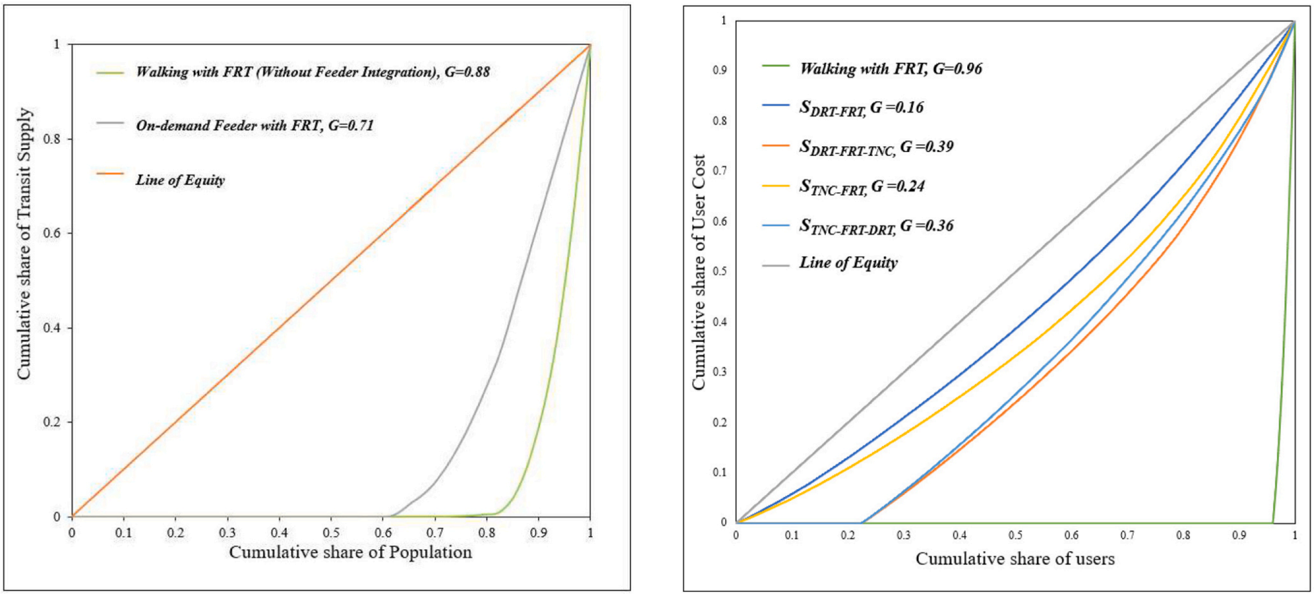


(b) Percentage of Population Served After Integration

Fig. 8. Transit Coverage Gap After Integration-Morristown.

4.2. Case study: Memphis

This case study demonstrates the application of the Accessibility-Radius concept to quantify the improvement of the existing FRT services following the introduction of on-demand services as feeders in Memphis. The transit agency responsible for the city's FRT system, the Memphis Area Transit Authority (MATA), implemented on-demand services to facilitate seamless connections with the existing FRT system and enhance the provision of first and last mile transportation. The project replaced a few of the the area's current low ridership FRT bus



(a) Lorenz Curve and Gini Index for Transit Supply (b) Lorenz Curve and Gini Index for User Cost

Fig. 9. Equity analysis.

routes with on-demand transit choices. They provided first and last-mile connectivity, in order to address the high maintenance costs and inefficiencies associated with these routes while ensuring adequate public transit accessibility in the area.

4.2.1. Transit coverage gap before on-demand

The comprehensive trip data was obtained from the transportation agency, and the dataset comprises 156,756 on-demand transit trips obtained throughout the period from July 1, 2021, to January 31, 2023. The study area encompasses a total of 52 zipcodes, which collectively have a population of 628,127 individuals.

Fig. 10b illustrates the potential transit demand for public transportation in different zip codes, categorizing the zip codes into Low, Low-Moderate, Moderate-High, and High demand based on their respective scores. The spatial distribution of demand in "High Demand" is apparent throughout 7 zip-codes. While, Fig. 10a displays the map of existing FRT routes and stops and their walking buffer prior to the introduction of on-demand service. This map shows 71 inbound routes with 4044 bus stops, representing the transit supply prior to any new service implementations. The resulting transit supply scores calculated by supply index method were categorized as Low, Low-Moderate, Moderate-High, and High. Fig. 10c shows that 25 zip codes within the area were served by FRT, with 10 zip codes having high transit supply. However, 27 out of the 52 considered zip codes were not covered by the existing transit supply, indicating potential inadequacy of public transportation for the people residing in those areas.

The transit coverage gap scores were computed based on these findings, and the resulting scores are depicted in Fig. 10d. The map illustrates the spatial distribution of transit coverage gaps in Memphis with the previously existed non-integrated FRT system. These coverage gaps are prevalent throughout the city, except in the central areas. The majority of the outlying areas of the city exhibit negative transit coverage gap scores, suggesting that the supply of public transportation is insufficient to meet the demand.

4.2.2. Transit coverage gap after integration

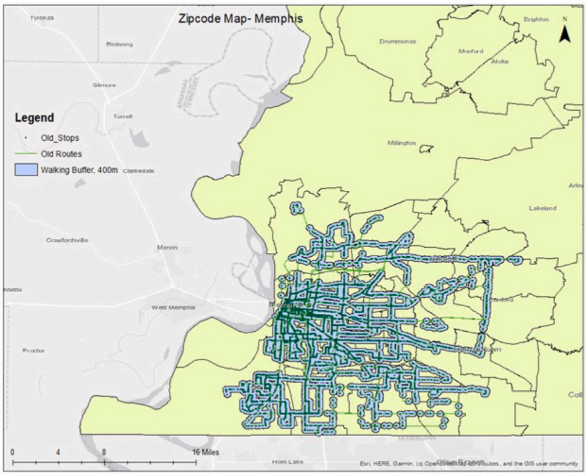
In order to assess the impact of this integration and determine the new transit supply, the study found that the 95th and 98th percentile distances for Accessibility-Radius as 0.45 miles (0.72 km) and 0.66 miles (1.06 km), respectively. These distances were used to establish the accessibility radii, as depicted in Fig. 11a. Given this increased accessibility-buffer zones, facilitating first and last-mile connections for on-demand services, the updated transit supply was calculated. By combining the new transit supply with the existing transit demand in the area, a revised transit coverage gap scores were determined, as shown in Fig. 11b. The introduction of on-demand services has led to a significant increase in transit coverage of the area. Specifically, the number of zip codes with positive coverage, has risen from 16 to 24 after the implementation of on-demand services. Moreover, this development has led to an impressive 224 % enlargement of the transit service coverage area.

5. Conclusion

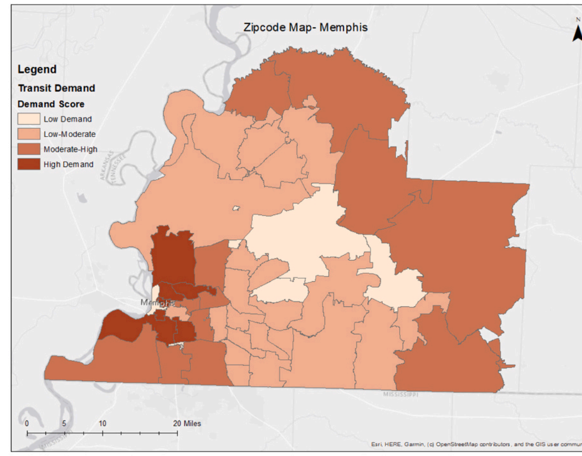
The rapid expansion of on-demand mobility in urban and suburban areas worldwide raises questions about its effectiveness in bridging the demand-supply gap in transit, yet there is little empirical evidence available on this matter. This study contributes to the current body of literature by evaluating the accessibility and equity effects of on-demand mobility services operating within an established FRT system as feeders. The spatial indicators employed in this study provide a nuanced understanding of accessibility changes at FRT bus stops post-integration with on-demand services. The findings emphasize the importance of evaluating the adaptability and benefits of integrated multi-modal transit systems.

By utilizing spatial indicators, specifically the novel metric introduced, "Accessibility-Radius", our research assesses the impact on accessibility, transit coverage gap, and equity under two separate scenarios: one with on-demand integration to FRT and one without. Employing an agent-based simulation, we created two scenarios: *Walking with FRT* and an integrated *On-demand Feeder with FRT*. In the former, the trip-maker is only permitted to use the FRT service to commute and walk within the walking buffer of the FRT stop. In the latter scenario, the trip-maker can utilize a feeder to reach these FRT stops, and thus, a greater number of trips will be able to access each FRT stop. Through an in-depth examination of existing public transportation accessibility and transit coverage gap scores, we identified priority service areas with unmet transportation needs based on sociodemographic indicators and the current FRT network.

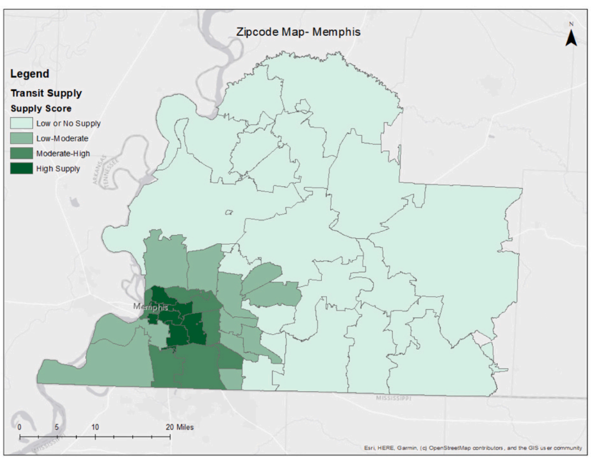
Our analysis calculated the generalized user cost for each trip, identified the successfully completed trips, and resulted in the



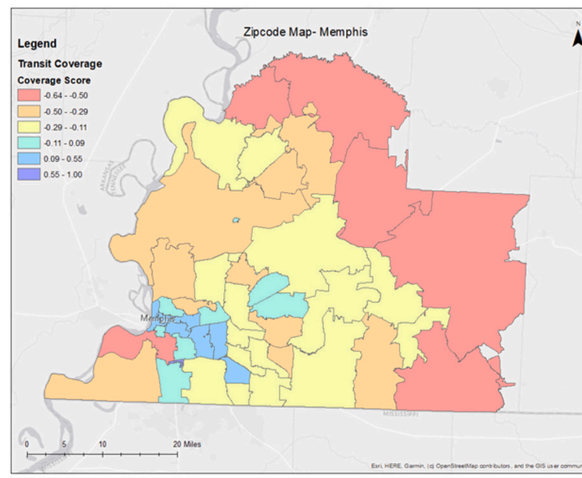
(a) Transit Network-Memphis



(b) Transit Demand-Memphis

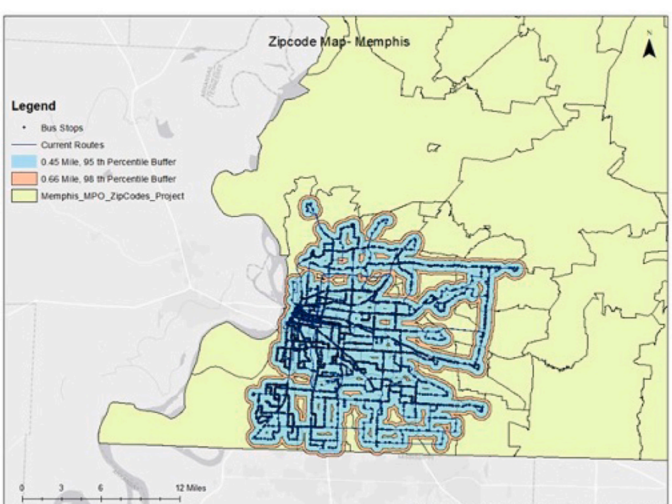


(c) Transit Supply-Memphis

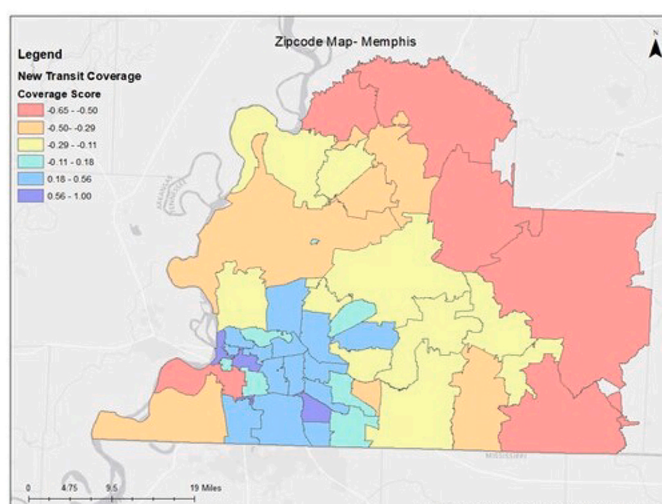


(d) Transit Coverage Gap before Integration-Memphis

Fig. 10. Transit characteristics before integration-memphis.



(a) Increased Accessibility-Radius after Integration-Memphis



(b) Transit Coverage Gap-Memphis

Fig. 11. Transit Coverage Gap after integration-Memphis.

formulation of the Accessibility-Radius. This radius was determined based on the 90th and 95th percentiles of distances between trip origins and the nearest FRT stops in the integrated scenario. This Ar becomes foundational for calculating the new transit supply. According to the new AR, the benefit of integration appears to operate well for origins within 4.85 km of the FRT stop in Morristown and 0.72 km in Memphis. The metric of AR provides additional insight into the spatial improvements in accessibility, highlighting the advantages of integration.

Through the analysis of the Morristown case study, this study incorporates the use of the Lorenz curve, Gini index, and Transit Coverage Gap to illustrate a significant enhancement in public transit accessibility. Specifically, the integration of on-demand feeders has resulted in a substantial increase in access, with the proportion of the population benefiting from public transit rising from 29.6 % to 45.2 %. However, challenges persist, particularly in the outer areas of the study region, emphasizing the need for continued improvements. The Lorenz curve method highlights major inequity in the existing transit system without integration, with a Gini Index of 0.88. Integration of the feeder into FRT significantly improves equity, reducing the Gini Index to 0.71. When trip accessibility was compared in terms of the generalized user cost, the *Walking with FRT* scenarios were the least equitable, while the On-demand feeder: $S_{DRT-FRT}$ scenario produced a strong equitable distribution in completing the trips with a Gini index of 0.16. To maintain an equitable public transportation system, every trip-maker from each origin and destination, regardless of geographic location, should have adequate integration options for completing the trip.

5.1. Limitation and future scope

The evident advantage of these integrated *On-demand Feeder with FRT* scenarios over the *Walking with FRT* scenario, demonstrates the viability of the presented methodology. From this perspective, using DRT and TNC as feeder systems for FRT is feasible. The present research has some limitations as we assume that all on-demand services are always available, and our analysis only considers the benefits of integration from the perspective of trip-makers. However, for large-scale viability, it is necessary to also consider the perspective of public transit agencies. Additionally, since we assumed uniform demand distribution within each spatial unit, more accurate results can be achieved by using smaller units, particularly in areas where demand is concentrated, as transit may effectively cover specific locations but not the entire spatial unit. Furthermore, the reliance on a single price cutoff, may overestimate the supply and accessibility benefits, highlighting the need for sensitivity analyses with varying price values in future research. While the integration of on-demand feeders into FRT was deemed beneficial, it is recommended to have further research to incorporate surge pricing and the fare variation for on-demand mobility based on trip time. This would enable the development of comprehensive, feasible implementation strategies and shed light on its effects on transit-reliant communities.

CRediT authorship contribution statement

Avani Aravind: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Suvin P. Venthuruthiyil:** Writing – review & editing, Validation, Methodology, Conceptualization. **Sabyasachee Mishra:** Writing – review & editing, Supervision, Resources, Methodology, Funding acquisition, Conceptualization.

Data availability

Data will be made available on request.

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