Research Article

TRR
JOURNAL OF THE TRANSPORTATION RESEARCH BOARD

Transportation Research Record
1–19

DOI: 10.1177/03611981231182706
journals.sagepub.com/home/trr
Sage

Evaluating Equity: A Method for Analyzing the Transit Accessibility of Affordable Housing Units

Jing Guo[1], Candace Brakewood[1], Ashley Hightower[1], and Christopher Cherry[1]

Abstract

Improving transit access for people in low-income communities is an important consideration for transit providers. However, there has only been a limited amount of research on the transit accessibility of affordable housing units. This paper aims to develop a method for evaluating the transit equity of existing affordable housing units and propose easy-to-implement modifications to local bus services to increase transit accessibility levels (assuming housing locations do not change in the short term). The proposed method has three steps, and it is applied to three cities in Tennessee with primarily bus-based transit systems. The first step measures the transit accessibility of specific affordable housing locations and citywide transit accessibility levels using a web-based platform built using open-source software. The second step evaluates the transit equity of affordable housing programs at the city level using Lorenz curves and Gini coefficients, and the transit equity of specific affordable housing locations by proposing a simple inequity index. The results reveal that the level of transit equity for affordable housing units differs across housing programs and cities. In the third step, an example of a modification to a local bus route is evaluated for one affordable housing location with a high inequity index to demonstrate the applicability of the method. The substantial increase in accessible jobs after modification, from 135 to 6,400, highlights the potential effectiveness of implementing short-term transit service changes to improve the accessibility of existing affordable housing locations. This three-step method primarily relies on open datasets that are also available for other regions in the U.S.A.

Keywords

public transportation planning, transit access/accessibility, affordable housing, transit equity

Previous research suggests that low-income people who cannot afford a personal vehicle often rely on public transit for their transportation needs (*1–3*). Many U.S. cities are automobile oriented, which presents significant mobility challenges for those who cannot or do not want to drive. Transit authorities in the U.S.A. play a critical role in providing essential mobility services to these often disadvantaged populations.

Along with transportation, housing expenses contribute to a significant financial burden on households, particularly those with low incomes. According to consumer expenditure statistics from the U.S. Bureau of Labor Statistics, housing and transportation are two major types of expenditure for U.S. households (*4*). However, some studies suggest that transit services tend to be more frequent and widespread in dense downtown areas (*5*) where housing prices are normally higher (*6*, *7*). Some low-income households that cannot afford high housing prices and private cars are often compelled to make trade-offs between housing and transportation costs. Therefore, the concept of affordable, accessible housing, which is inexpensive housing in walkable urban neighborhoods, has been proposed to improve transit equity for low-income households (*8*).

[1]Department of Civil and Environmental Engineering, University of Tennessee, Knoxville, TN

Corresponding Author:
Candace Brakewood, cbrakewo@utk.edu

In the U.S.A., some supply-side affordable housing programs are administered by the federal government, for example, Low-Income Housing Tax Credits (LIHTC), Multifamily Subsidized Housing (Multifamily), and Public Housing (PH). The overall purpose of such housing programs is to make rent more affordable for low-income households. However, affordable housing units are sometimes planned without consideration of transit accessibility as an evaluation criterion, which is partly because of the absence of federal requirements for planning affordable housing as well as the lack of coordination between housing authorities and transit agencies (*1*). Furthermore, a recent study from the Transit Cooperative Research Program concluded that many transit agencies often do not specifically prioritize serving neighborhoods with high levels of affordable housing in their transit planning process (*1*, *9*).

Previous studies suggest there is a need to develop systematic practical guidance and effective approaches that can be implemented by transit agencies and housing authorities to promote the coordination of transit services with affordable housing (*1*, *9*). However, housing construction, especially large apartment complexes, and fixed rail transit (such as subway and light rail) are durable and permanent infrastructure investments; bus routes are considerably more adaptable and can be (relatively) easily modified to improve transit accessibility. Therefore, modifications to local bus routes that can be implemented in the short term (e.g., within a few weeks or months) provide an important first step toward potentially increasing transit accessibility for existing residents who live in affordable housing situated in areas that are underserved by public transit.

By quantifying transit accessibility in areas with existing affordable housing units, this research contributes to the literature in two important ways. First, the paper proposes a systematic three-step method for comparing the transit equity of existing affordable housing units and for evaluating potential short-term bus service modifications that could increase transit access levels. Second, this three-step method relies primarily on open datasets, specifically, General Transit Feed Specification (GTFS) data, and affordable housing locations obtained from the U.S. Department of Housing and Urban Development (HUD), which makes this method widely applicable to other regions of the U.S.A. that have fixed-route transit services.

Literature Review

The following sections briefly review the relevant literature pertaining to transit accessibility and transit equity.

Transit Accessibility

Transit accessibility refers to a person's ability to reach opportunities via transit (*10*). Several studies published in the last decade have focused specifically on transit accessibility (*11–14*). The following section reviews previous research on transit accessibility from the perspective of measurement methods and factors that contribute to calculation accuracy.

Transit Accessibility Measures. Transit accessibility measures can generally be grouped into two categories: opportunity-based measures (also known as primal measures); and time- or cost-based measures (also known as dual measures) (*15*). Opportunity-based measures are the most commonly used method in previous research (*16*). These require a pre-assumed cutoff travel time that has no standard value under different scenarios (*16*). Previous research employing opportunity-based measures has often been conducted in situations in which individuals have multiple options, such as job opportunities (*15*, *17*). Commonly used opportunity-based measures include the cumulative opportunity measure, the weighted cumulative opportunity measure, and the competitive access measure; each of these measures is briefly described in the following paragraphs.

The cumulative opportunity measure is the most popular of the opportunity-based measures in previous research (*14*, *18*). A cumulative opportunity metric measures the number of opportunities, such as jobs, that a person can reach within a given period of time (e.g., 60 min) via transit service. The cumulative opportunity measure has been used in many previous studies because of its minimal data requirements, ease of comprehension, and consistent interpretation across different times and locations, which enables greater comparison, tracking, and benchmarking (*16*). For example, one recent study of the San Francisco Bay Area in California applied the cumulative opportunity measure in a transit accessibility analysis that calculated the total number of jobs accessible within 40 min of transit travel time during a.m. peak hours (7:00 to 10:00 a.m.) (*19*).

The weighted cumulative opportunity measure (also known as the gravity-type measure) is converted from the cumulative opportunity measure by adding weights to all the opportunities using a specific impedance function (e.g., distance decay functions, time decay functions, or cost decay functions), making opportunities with higher impedances from a certain location less attractive (*16*, *20*). For example, one relevant study conducted in Detroit calculated transit accessibility to jobs by using an impedance function of travel cost (*21*). Although the weighted cumulative opportunity measure can describe human behavior better, it is more challenging to interpret than the cumulative opportunity measure because the impedance formula can vary from time to time and from location to location (*16*, *22*).

The competitive access measure is another opportunity-based measure that considers the competition between travelers and opportunities (*16*). For example, a study of the Boston area proposed a competitive access measure model that included competition at workplace locations to measure the employment accessibility of low-income workers (*23*). The competitive access measure has been widely used in research on measuring transit accessibility (*24–26*). However, compared with the cumulative opportunity measure, the competitive access measure requires more computation and may be more difficult to apply and understand in real-world practice (*16*).

In contrast to the previous approach of calculating the number of opportunities that can be reached within a given time threshold, time- or cost-based measures calculate travel time or cost to achieve a fixed number of opportunities. Depending on the preset number of opportunities, this approach can be further divided into time- or cost-based measures for a single opportunity and multiple opportunities. For the single opportunity measure, the number of opportunities is one, whereas for the multiple opportunities measure, the threshold is two or more. This measure is often used when the time to access the opportunity and the cost of doing so are more important than the number of opportunities accessible (*15*). As an example, Farber et al. (*27*) measured accessibility to food stores in Cincinnati by calculating the travel time from each census block to the one nearest supermarket and the three closest supermarkets. Similar approaches have been successfully applied to measure the accessibility of other essential services, as one recent study of healthcare accessibility in Florida has done (*28*). Time- or cost-based measures provide a straightforward way of comparing transit accessibility levels between different locations and cities. They may also be more easily understood by the public because measuring access in minutes provides an easy-to-interpret scale (*16*). However, without a suitable reference point, determining a threshold number of opportunities beyond one may be challenging for time- or cost-based measures (*16*). Furthermore, travel time alone may not fully capture people's needs or preferences (*16*). For example, individuals may prefer to shop at a supermarket that is not necessarily the closest one to their home.

In this study, the cumulative opportunity accessibility measure will be selected to estimate transit accessibility to jobs because it is easier to compute and interpret in practice and, therefore, more likely to be adopted by planning agencies.

Spatial and Time Resolution of Transit Accessibility. The accuracy of accessibility calculations usually depends on two factors: spatial resolution and time resolution.

The spatial resolution of origins and destinations is an essential factor that could affect the results of accessibility studies. Many previous studies use the centroid points of arbitrary zones as the origin to calculate transit accessibility (*11*, *15*). However, the transit accessibility of the centroid point might not represent the average transit accessibility level in that zone. In response to this problem, some methods now use a higher spatial resolution in which origins and destinations can be a rectangular grid cell for each region, which is the case with the open-source "Analysis" platform from Conveyal utilized in this study (*29*). To improve the accuracy and representativeness of citywide transit accessibility, this paper utilized every rectangular grid cell in the region as the origin in the calculations.

Another essential factor that could affect accessibility results is time resolution (*16*). Transit accessibility is schedule dependent (*16*) and could be highly variable over time (*14*). Some previous studies have only considered the service frequency (e.g., number of vehicle trips per week) (*30–32*) or the transit accessibility at a single departure time (*11*, *15*). However, transit accessibility at one time point might not be representative. The common solution is to sample multiple time points and compute the average or the median travel time across the sample of time points (*16*). To prevent the results from being influenced by a specific time point, this study utilized a schedule-based accessibility measurement that takes the median of results from multiple time points (*29*).

Transit Equity of Affordable Housing

Equity is generally divided into two categories: ***horizontal equity***, which emphasizes the equal distribution of resources between individuals and groups; and ***vertical equity***, which suggests that the supply of resources should be based on needs and abilities (*33*). In the field of transit, vertical equity aims to provide transit access to those with the greatest need (*31*). Many previous studies on transit vertical equity have evaluated the distribution of transit accessibility among disadvantaged groups, which are categorized by demographic characteristics such as low-income households, no-car households, or elderly groups (*31*, *34*, *35*). A few previous studies have considered the transit equity of affordable housing units where low-income populations often reside.

The purpose of affordable housing programs is to make the rent for low-income households more affordable. However, it is often unknown whether affordable housing programs provide equitable transit access. Therefore, the transit equity of affordable housing programs (regionwide) and the transit equity of affordable housing locations (specific locations within a region) should be measured. One relevant previous study evaluated regionwide transit equity across affordable housing programs in Baltimore by applying Lorenz curves and Gini coefficients (*12*). Lorenz curves are commonly applied in a range of disciplines to represent a quantity that can be accumulated across a population graphically (*31*). The Gini coefficient can be used as a mathematical metric to quantify the system-wide degree of inequity by calculating the ratio of the area between the line of equity and the Lorenz curve (*36*), and has been used in some previous studies (*30*, *31*, *37*, *38*). This paper adopts a similar method for evaluating the transit equity of affordable housing programs at the city level. However, the above-mentioned Baltimore study (*12*) only used the Lorenz curve and the Gini coefficient and lacks a measurement of transit equity for specific affordable housing locations. To fill this gap, the paper expands the analysis of transit inequity to consider specific locations of affordable housing units within a region.

The key point of measuring transit equity for specific locations within a region is to understand the relationship between transit supply and transit demand. A place with high demand and low supply will be defined as inequitable (*32*). Transit demand in this analysis is measured as the percentage of existing affordable housing units at a specific location, which has rarely been considered in previous studies. Therefore, this paper proposes a simple inequity index that calculates the ratio between the percentage of existing affordable housing units and the percentage of jobs accessible within a 60-min transit trip for each affordable housing location. This inequity index is a straightforward measure of the relative relationship between transit demand and transit supply and can easily be applied in practice.

Objectives

The following summarizes the three objectives of this study.

- Objective 1: Evaluate the transit equity of existing affordable housing programs at the city level.
- Objective 2: Evaluate the transit equity of specific affordable housing locations and identify specific affordable housing locations that have inequitable transit access within the city.
- Objective 3: Propose short-term transit service modifications with the potential to increase transit accessibility for existing affordable housing locations.

Background and Case Studies

Background on Affordable Housing

Housing costs are the highest share (34.9% in 2020) of average annual expenditure for U.S. households (*4*). To help alleviate the burden of housing costs for low-income households, numerous affordable housing programs are administered by the U.S. federal government. One well-known program is known as LIHTC (*39*), also known as Section 42, which issues tax credits for the development of affordable housing for low-income households. Two other programs considered in the following analysis are Multifamily and PH, which are both rental assistance programs administered by HUD that provide decent and safe rental housing for eligible low-income households (*40*, *41*). These are the three largest federally funded supply-side programs (*42*) with the overall purpose of making rent for low-income households more affordable. Geospatial datasets for these affordable housing programs are publicly available from the HUD-eGIS Storefront (*43*). Therefore, they have been selected for analysis in this study.

The Qualified Allocation Plan (QAP) is the federally mandated standard for evaluating all housing projects that apply the federal LIHTC program (*44*). Each state in the U.S.A. is required to design and implement a QAP, which specifies the sociospatial selection criteria that are applied to affordable housing for low-income people (*44*, *45*). For example, three points will be awarded to a housing building if it is located within 1,500 feet of a regular public bus stop or rapid transit system stop in some states (*45*). Because many low-income people depend on transit for their transportation needs (*46*), scoring criteria related to transit accessibility (e.g., proximity to transit stops and transit access to jobs) are used in some states, for example, California, Connecticut, Virginia, and Georgia (*45*, *47*).

Background to the Case Studies

Previous studies on transit accessibility and housing affordability primarily focused on dense cities with robust transit networks, for example, recent studies of Baltimore (*12*), Chicago (*48*), San Diego (*49*), Orange County, California (*50*), and Houston (*51*). However, additional research on low-income populations living in lower-density heavily automobile-oriented cities, such as those in Tennessee, is needed. According to the U.S. Census Bureau, about 60% of transit commuters in Tennessee are low-income workers earning less than $24,999 per year (*52*), which suggests that transit plays a vital role in providing critical transportation services to low-income communities.

Moreover, this paper is particularly relevant for Tennessee because the Tennessee Housing Development Agency's most recent QAP for low-income housing credits does not consider transit access in the process of allocating credits for affordable housing (*53*). This suggests there is a need to develop a method for systematically evaluating the transit accessibility levels of existing affordable housing units that policymakers and practitioners can use. The proposed case studies demonstrate the significance of the work and its potential applicability to other urban areas in the U.S.A. that are facing similar issues.

This research focuses on three large cities in Tennessee, namely, Nashville, Chattanooga, and Memphis, which all have predominantly automobile-oriented transportation systems with bus-based public transit systems. However, these three cities differ from one another with regard to population size, housing policies, demographics, and economic characteristics. Nashville is a very large population center that has experienced significant economic growth and gentrification over the last decade, and it currently ranks as the 21st most populous city in the U.S.A. according to the most recent data from the U.S. Census Bureau (*54*). It should also be noted that PH is not included among the affordable housing programs in Nashville. Chattanooga is a relatively small city that in recent years has experienced economic growth and gentrification, particularly in its downtown area (*55*). Compared with the other two cities, Memphis has a higher rate of poverty, a higher rate of crime, and a slower rate of economic growth (*54*, *56*).

In the remainder of this paper, the transit equity of existing affordable housing programs in these three cities is first evaluated and compared between cities. Then, for each city, specific affordable housing locations with inequitable transit accessibility are identified and ranked by inequity index values. Finally, a specific affordable housing location in the city of Memphis is selected to demonstrate the process of proposing and evaluating short-term modifications to the transit service.

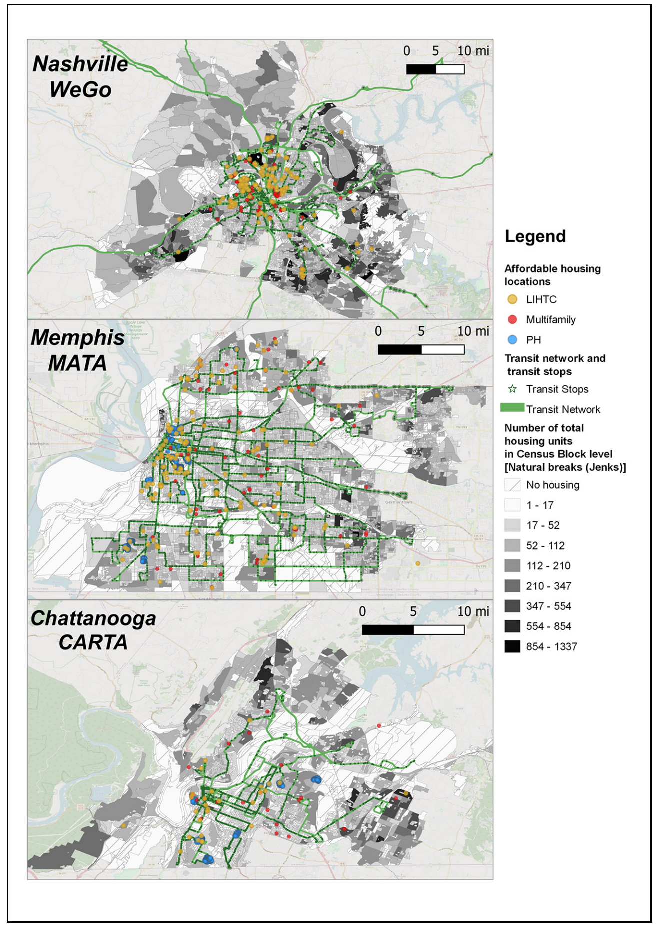

Figure 1. Maps of the three study areas (Nashville, Memphis, Chattanooga) showing the transit networks, locations of affordable housing, and the total number of housing units in each census block.
Note: MATA = Memphis Area Transit Authority; CARTA = Chattanooga Area Regional Transportation Authority; LIHTC = Low-Income Housing Tax Credits; PH = Public Housing.

Data

This section discusses the data used to measure the transit accessibility and transit equity of affordable housing units. Figure 1 presents maps of the three case studies, including the transit network (shown as green lines), the locations of affordable housing (including LIHTC, Multifamily, and PH), and the total number of housing units in each census block.

Origins Data (Affordable Housing Locations)

The affordable housing programs selected for this study are LIHTC, Multifamily, and PH. Geocoded affordable housing locations with the number of housing units were extracted from HUD (*43*).

Destinations Data (Jobs Locations)

Various datasets provide job information nationally or regionally. The Longitudinal Employer–Household Dynamics Origin–Destination Employment Statistics (LODES) dataset provides the home and work locations of employed people living in the U.S.A. at the census block level, and is commonly used to obtain information about workers and jobs (*17–19, 57*). For this study, the geospatial locations of the jobs were obtained from the latest version of LODES, that is, 2018. Because more recent data were not available, it was assumed that job locations were stable from 2018 to 2022.

Transit Network

GTFS data have been applied in previous literature on transit accessibility to estimate travel times from one point to another at different times of the day (*58*). Furthermore, the standardization of GTFS data makes it possible to analyze transit accessibility between

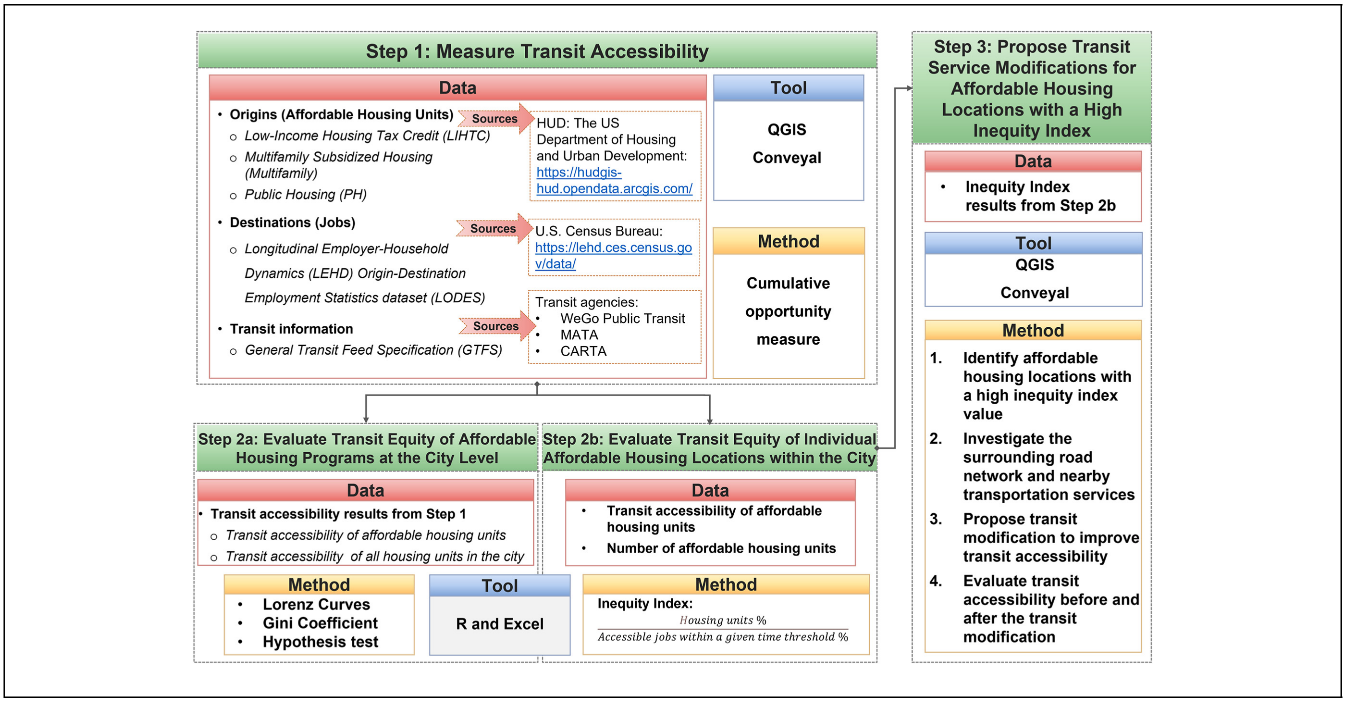

Figure 2. Conceptual framework of the methodology.
Note: MATA = Memphis Area Transit Authority; CARTA = Chattanooga Area Regional Transportation Authority; QGIS = Quantum Geographic Information System.

different cities (*14*, *59*). The GTFS datasets, including static transit schedules and geospatial transit networks in 2022 for three Tennessee cities (Nashville, Memphis, and Chattanooga), were collected from the Nashville Metropolitan Transit Authority (WeGo), Memphis Area Transit Authority (MATA), and Chattanooga Area Regional Transportation Authority (CARTA).

Geographic Layer for Measuring Citywide Transit Accessibility

To measure the transit accessibility for citywide total housing units, the 2020 TIGER/Line shapefile of census block boundaries (the most detailed level recording the number of housing units) was obtained (*60*). The origins for measuring citywide transit accessibility are grid cells (with a resolution of 306 m [1002 ft] cell width [measured at the equator] or 216 m [709 ft] cell width [measured at the 45° latitude]). The transit accessibility for total housing units within a census block was derived by calculating the average transit accessibility of each grid cell within the block.

Methodology

This section discusses the proposed method. Figure 2 shows the conceptual framework, which is divided into three steps. Step 1 measures the transit accessibility of affordable housing locations and the citywide transit accessibility of all housing units in a city. Step 2 evaluates the transit equity of affordable housing programs at the city level by applying Lorenz curves and Gini coefficients, and it also identifies specific affordable housing locations within the city that have inequitable transit access by applying a simple inequity index. Step 3 demonstrates the process of proposing and evaluating possible transit service changes that can be implemented in the short term (e.g., for buses) for an existing affordable housing location with a high inequity index.

Step 1: Measure Transit Accessibility

Figure 3 shows the configuration for measuring transit accessibility using the Conveyal Analysis platform. Two origin sets were used in the transit accessibility analysis: one was affordable housing locations; the other was grid cells of each of the three cities. The spatial resolution (cell width) of grid cells is 306 m (1002 ft) (measured at the equator) or 216 m (709 ft) (measured at the 45° latitude). The following assumptions were made: transit vehicle departures were between 7:00 a.m. and 10:00 a.m. on a weekday; transit stops were accessed by walking; fixed-route transit trips were taken with a maximum of three transfers (considered to encompass most practical trips [*61*]); and walking was used to egress from transit stops to the destination. The maximum travel time was 60 min, which was selected because 74% of Tennessee's transit

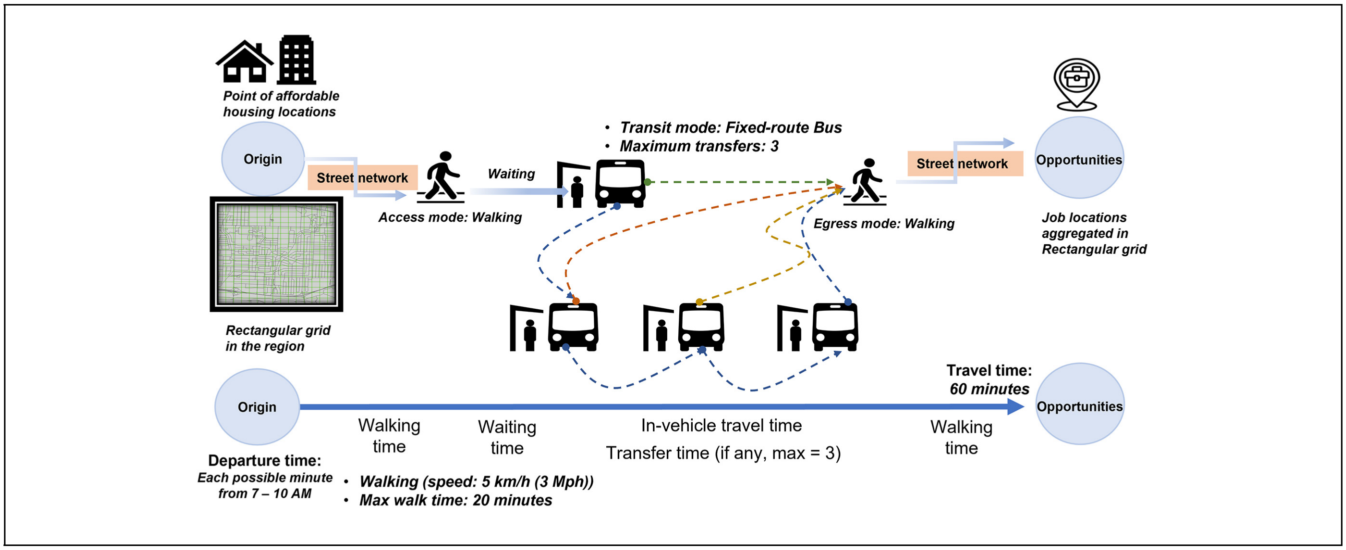

Figure 3. Configuration for transit accessibility calculation.

commuters travel for less than 60 min to get to work (*52*). The maximum walking time was set at 20 min, and the walking route followed the street network developed by OpenStreetMap. A schedule-based algorithm in the Conveyal Analysis platform calculated the number of jobs accessible via walking and transit from each origin at every minute between 7:00 a.m. and 10:00 a.m. and then exported the median value of transit accessibility for all minutes as the result.

This paper applied the cumulative opportunity measure, which calculated the number of jobs accessible via transit from given origins within a specific time threshold, as shown in Equations 1 and 2.

$$A_i = \sum_j O_j f(C_{ij}), \quad (1)$$

$$f(C_{ij}) = 1, \text{ when } C_{ij} \leq t, \text{else } f(C_{ij}) = 0 \quad (2)$$

where
A_i is the transit accessibility from origin i, O_j is the number of opportunities available at destination j, C_{ij} is the travel cost from i to j, and $f(C_{ij})$ is an impedance function, which equals 1 when travel costs less than the given time threshold t and equals 0 otherwise. In a pedestrian access analysis, walking speed is generally assumed as 5 km/h (3 mph) based on previous experience (*16*).

Step 2a: Evaluate Transit Equity of Affordable Housing Programs at the City Level

The aim of this step is to (a) evaluate horizontal equity, which investigates whether there is an equal distribution of transit accessibility among affordable housing units in different subsidized housing programs, and (b) evaluate vertical equity, which determines whether affordable housing programs provide more equitable transit accessibility compared with the citywide total housing or randomly selected housing units.

The transit equity of affordable housing programs at the city level was evaluated by applying Lorenz curves and Gini coefficients. Figure 4 shows an example of a Lorenz curve for the transit accessibility distribution among a population. The diagonal is the equity line, which presents the equal distribution of cumulative transit access among the population. The curved line is an example of a Lorenz curve, which represents an inequitable distribution of transit access among the population. In this example, 70% of the population share only about 15% of the population's transit supply. The ratio of the area between the equity line and the Lorenz curve (dot shaded area m in Figure 4) divided by the total area under the equity line (dot shaded area m plus slash shaded area n in Figure 4) is mathematically presented by the Gini coefficient (*36*).

Equation 3 shows the approximate mathematical calculation of the Gini coefficient (*62*):

$$G_j = 1 - \sum_{i=1}^{n} (Y_i + Y_{i-1}) * (X_i - X_{i-1}) \quad (3)$$

where

- Y_i is the cumulative proportion of the transit accessibility, $i = 0, \ldots, n$, $Y_0 = 0$, $Y_n = 1$,
- X_i is the cumulative proportion of the population, $i = 0, \ldots, n$, $X_0 = 0$, $X_n = 1$, and
- G_i is the Gini coefficient for a sample j.

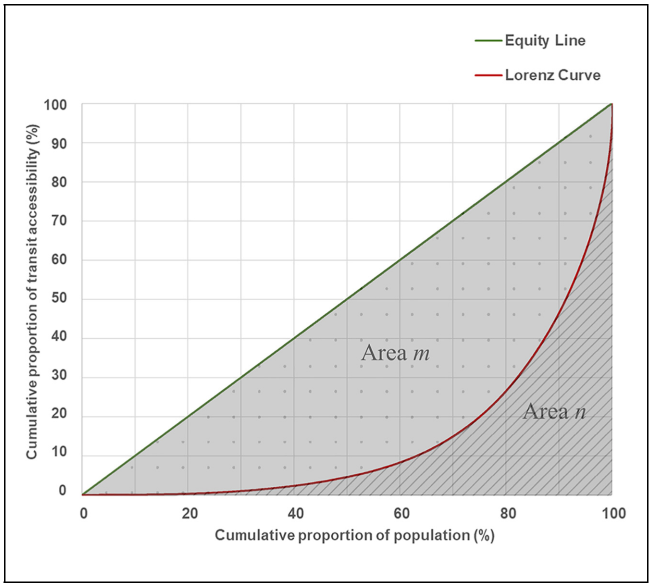

Figure 4. Example of Lorenz curves of transit accessibility distribution among a population.

In the case of measuring transit equity among affordable housing programs, the Lorenz curve represents the cumulative distribution of transit-accessible jobs across the citywide total housing and affordable housing units, respectively.

Based on the context of this study and the objectives for this step of the method, a desirable outcome with regard to vertical equity would be that the Gini coefficients are lower for affordable housing units compared with the citywide total or randomly selected housing, and that the Lorenz curve of affordable housing units is closer to the equity line (above the Lorenz curves of citywide total housing or randomly selected housing).

Step 2b: Evaluate Transit Equity of Specific Affordable Housing Locations within the City

The next steps uses the simple inequity index shown in Equation 4. The numerator (the percentage of housing units for a specific location *i*) was defined as the number of affordable housing units at location *i* (e.g., within a large apartment complex) divided by the total number of affordable housing units in the city. The denominator (the percentage of jobs accessible with a 60-min transit trip) was defined as the number of transit-accessible jobs from the affordable housing location *i* divided by the cumulative number of transit-accessible jobs in all affordable housing locations within the city. This inequity index is a straightforward measure of the relative relationship between transit demand and transit supply and can be easily applied in practice. A higher inequity index indicates a higher demand (a higher number of affordable housing units) and a lower transit supply (a lower number of transit-accessible jobs).

$$\text{Inequity index}_i = \frac{\text{Percentage of affordable housing units at location } i}{\text{Percentage of transit accessible jobs within a given time threshold at location } i} \quad (4)$$

To analyze the transit equity of affordable housing programs at the city level, a hypothesis test was used to determine whether the Gini coefficient of affordable housing units was significantly different from the mean Gini coefficient of randomly selected housing units in a specific city. Citywide total housing includes houses, apartments, mobile homes, groups of rooms, and single rooms occupied or intended for occupancy as separate living quarters (*63*). The number of housing units randomly selected from citywide total housing was set equal to the combined total number of housing units in the three affordable housing programs (LIHTC, Multifamily, PH) in that city. Fifty random samples were created for each city. The hypothesis test applied the 99% confidence interval and the two-tailed *t*-test. The null hypothesis H_0 was that the mean Gini coefficient of randomly selected housing units is equal to the Gini coefficient of affordable housing units, and the alternative hypothesis H_1 was that the mean Gini coefficient of randomly selected housing units is not equal to the Gini coefficient of affordable housing units.

Step 3: Propose Transit Service Modifications for Affordable Housing Locations with a High Inequity Index

Step 3 aims to propose short-term transit service changes that can easily be applied in practice to existing affordable housing locations with limited transit access. Within the Conveyal Analysis platform, the following transit service modification types can be selected: converting frequency; adding a trip pattern; adjusting dwell time; adjusting speed; removing stops; removing trips; and rerouting (*64*). The "converting frequency" modification can modify the transit vehicle's headway by editing the timetables. The "adding a trip pattern" modification enables new trip patterns to be added to a scenario. The "adjusting dwell time" modification allows for changes in the dwell time at a specific stop or along a route. The "adjusting speed" modification can adjust the transit vehicle's speed on an entire route or just a route segment. The "removing stops" modification can remove some of the stops from a route. The "removing trips" modification is used to remove entire routes or remove specific trip patterns on a particular route. The "rerouting" modification can be used to represent detours, extensions, and curtailments (*64*).

The surrounding road network and nearby transit services were investigated before selecting one or more of these transit service changes in the software. For example, increasing the frequency would be selected if the walking distance to the nearest transit stop from the housing unit was relatively short but the headway of transit service was poor. For the specific affordable housing locations under consideration, various transit service modifications can be selected from this list and then analyzed in relation to a "comparison scenario" as the baseline. For the example used in this paper to demonstrate the method, the "converting frequency" modification was selected. Then, the transit accessibility level from the affordable housing location under the new scenario (e.g., increased transit frequency for the example shown in the results section) was calculated by applying the method described in Step 1. The platform then provides an isochrone map and numerical outputs for the change in the number of accessible job opportunities after each transit service modification. This simulation process in the Conveyal Analysis platform makes it easy to evaluate many different possible transit modifications before one is selected for implementation.

Case Studies and Results

This section presents the results of the three-step method applied to the case studies of Nashville, Memphis, and Chattanooga.

Results of Step 1: Transit Accessibility Results

Figure 5 provides a visual representation of the distribution of transit accessibility levels at all affordable housing locations by displaying citywide transit accessibility levels and affordable housing locations in the three cities. The darker the purple area, the lower the transit accessibility in that area. Transit accessibility was grouped by quantile (equal count) classification. The housing locations of LIHTC units, Multifamily units, and PH units are shown as yellow circles, red circles, and blue circles, respectively. As can be seen from the figure, compared with other cities, Nashville had the greatest range of variation in transit accessibility throughout the city, which may be related to Nashville being a consolidated city/county that also contains large areas of rural and undeveloped land. It should also be noted that compared with Chattanooga, Memphis had more affordable housing units.

These maps suggest that even though the majority of affordable housing was located in green areas with relatively good access to transit, there was still some located in purple areas with relatively low access to transit.

Results of Step 2a: Lorenz Curves and Gini Coefficients

Table 1 shows the results of transit accessibility calculations and the Gini coefficient for citywide total housing, random samples, and affordable housing units in Nashville, Memphis, and Chattanooga. The number of housing units randomly selected from citywide total housing is equal to the combined total number of affordable housing units in all three housing programs (LIHTC, Multifamily, PH) in that city. Generally, on average, affordable housing units had a higher level of transit accessibility than both citywide total housing and randomly selected housing units. Comparing the Gini coefficient of each affordable housing program separately, transit accessibility was more equitably distributed among Multifamily units than among units of other programs (LIHTC or PH). In Memphis and Chattanooga, the distribution of transit accessibility of the combined total of affordable housing units was less equitable than that of affordable housing units in any single program. This result indicates that transit resources were unevenly distributed among different affordable housing programs in Memphis and Chattanooga. This same result is shown in Figure 6, in which the red solid line, which represents the Lorenz curve for combined affordable housing programs, lies below all dashed lines that represent the Lorenz curves for LIHTC units, Multifamily units, or PH units for Memphis and Chattanooga, whereas it lies between the two dashed lines for Nashville. The closer the Lorenz curve is to the equity line, the more equitable the transit accessibility distribution.

Table 2 provides the hypothesis test results within the 99% confidence interval and two-tailed *t*-test. The results of rejecting the null hypotheses and comparing the Gini coefficients indicate that transit access is distributed more equitably among each affordable housing program than if the housing units were randomly distributed within the city (with the exception of LIHTC units in Nashville). Given the results in Table 1, the Gini coefficient of the combined total of the affordable housing programs is higher than the sample mean of random housing units in Memphis, suggesting that transit accessibility is distributed less equitably among affordable housing units than if the housing units were randomly selected; however, the opposite is true for Nashville and Chattanooga. This suggests that affordable housing units in Memphis may be more dispersed, with some housing in areas with good transit access and other housing in areas with poor transit access, and that some of the affordable housing locations may have high levels of transit inequity.

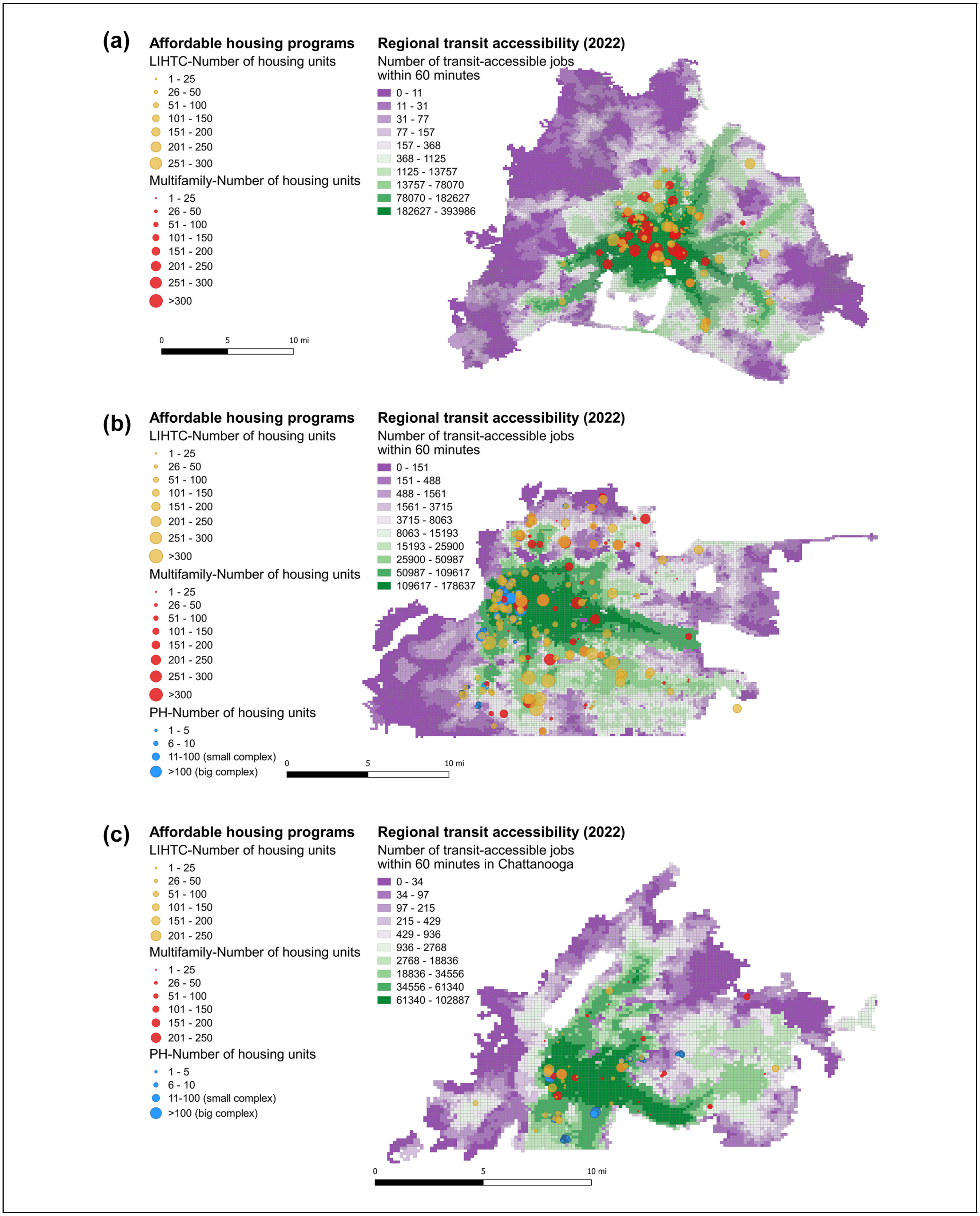

Figure 5. Transit accessibility and affordable housing locations in three cities: (*a*) Nashville, (*b*) Memphis, and (*c*) Chattanooga.
Note: LIHTC = Low-Income Housing Tax Credits; PH = Public Housing.

Table 1. Results of Transit Accessibility and Gini Coefficient

Housing types	Number of housing units	Average transit accessibility	Gini coefficient
Nashville			
Citywide total housing	316,363	116,979	0.8370
Random samples	15,509	117,123	0.8338
Combined affordable housing programs*	15,509	160,665	0.7039
LIHTC	6,482	144,222	0.8350
Multifamily	9,027	204,414	0.4299
Memphis			
Citywide total housing	286,713	64,101	0.7230
Random samples	26,657	64,473	0.7241
Combined affordable housing programs	26,657	93,270	0.8950
LIHTC	15,602	76,890	0.6817
Multifamily	6,905	64,635	0.6379
PH	4,150	96,745	0.6703
Chattanooga			
Citywide total housing	85,266	46,719	0.7711
Random samples	6,099	46,650	0.7646
Combined affordable housing programs	6,099	53,140	0.7154
LIHTC	2,267	68,173	0.5138
Multifamily	1,685	57,643	0.4502
PH	2,147	51,959	0.4596

Note: LIHTC = Low-Income Housing Tax Credits; PH = Public Housing.
*Nashville does not have PH.

Results of Step 2b: Identify Affordable Housing Locations with Inequitable Transit Accessibility

Next, the inequity index was calculated for each affordable housing location within the city to identify specific locations that have inequitable transit access. Table 3 lists the five affordable housing locations with the highest inequity indices in each of the three cities. Overall, among these affordable housing locations, Nashville had a higher level of inequitable transit accessibility.

Figure 7 shows the five affordable housing locations listed in Table 3 on a map for each city; also included are the transit network (stops and routes) and transit accessibility levels (shaded in green to purple, as in previous figures). Figure 7 reveals that many of the affordable housing locations that scored poorly on the inequity index were in areas with low transit accessibility that also had substantial walking distances to the nearest transit stop. For affordable housing located away from transit stops, rerouting or extending transit routes may be a reasonable modification to improve accessibility. However, rerouting is dependent on funding, requires long-term planning, and can diminish overall transit operational efficiency. For affordable housing locations near transit stops (e.g., Wesley Highland Meadows in Memphis, shown in Figure 7*b*), the limited transit service frequency may be the cause of low transit accessibility levels, and a short-term schedule modification that increases frequency can be applied to improve transit accessibility in practice. In the following example, the results of Step 3 illustrate the process of proposing and evaluating a short-term schedule modification (specifically, increasing frequency/decreasing headway) to an existing affordable housing location with a high inequity index.

Results of Step 3: Propose and Evaluate Transit Service Modifications for Existing Affordable Housing Locations with a High Inequity Index

This section demonstrates the process of proposing and evaluating transit service modifications for a single affordable housing location in Memphis known as Wesley Highland Meadows. One of the reasons this affordable housing location was chosen for in-depth study is that modifications to the nearest transit route (#40) have already been proposed in a local planning document known as the Memphis Transit Vision (*65*). The Memphis Transit Vision includes a redesign of the existing transit system and was produced with significant involvement from the public, stakeholders, and elected officials who believe that if it were to be funded, the proposed transit system redesign will significantly improve transit accessibility to jobs (*65*). The Wesley Highland Meadows example was chosen not only to demonstrate the methodology for researchers, but also to show its real-world use in assisting transit agencies, local planners, and policymakers to assess proposed transit modifications.

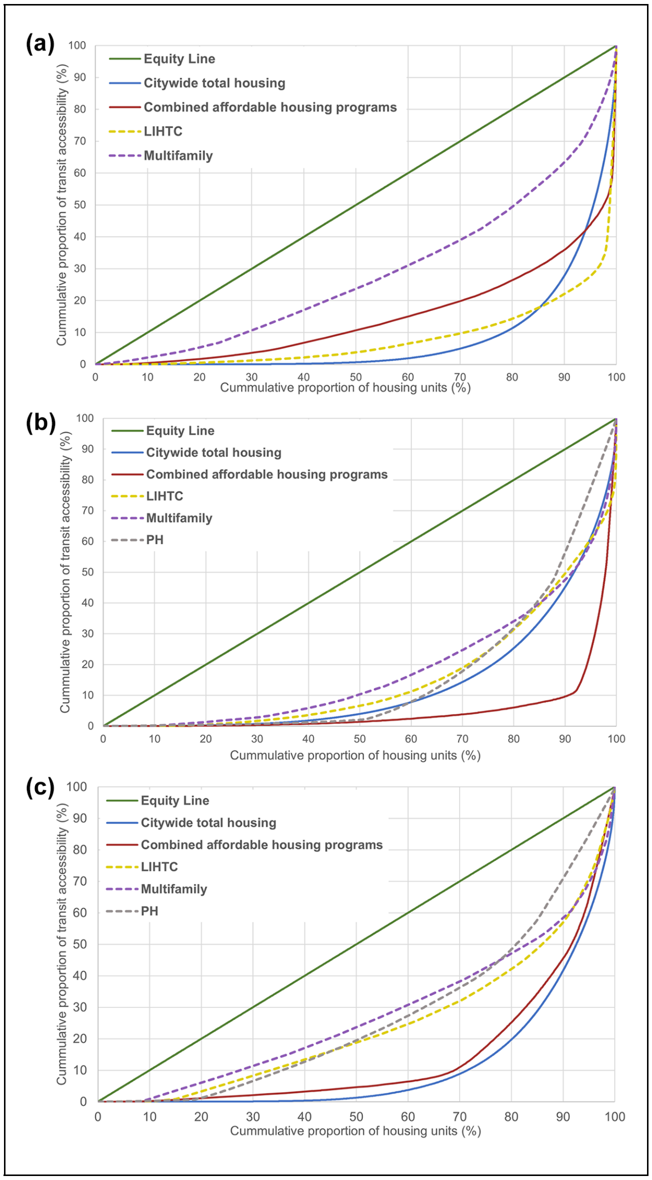

Figure 6. Transit accessibility Lorenz curves by type of affordable housing programs in three cities: (*a*) Nashville, (*b*) Memphis, and (*c*) Chattanooga.

Note: LIHTC = Low-Income Housing Tax Credits; PH = Public Housing.

Figure 8 shows a map of Wesley Highland Meadows relative to the nearby MATA Route 40 (red line), the nearby transit stops (black squares), and the walking path between the closest transit stop and the affordable housing location (black dashed line). Wesley Highland Meadows is 0.4 mi (8 min walking) from the nearest transit stop, indicating relatively good spatial access to transit. Route 40 has a headway of 90 min during the a.m. peak hour (7:00 a.m. to 10:00 a.m.), during which three buses depart from and two buses depart toward the downtown direction. Therefore, it could be concluded that a large headway of transit vehicles may be one cause of low accessibility levels.

The draft recommended transit network developed by the Memphis Transit Vision proposes decreasing the headway of Route 40 from 90 min to 60 min. Therefore, in this example, the proposed transit service modification is to decrease the headway of Route 40 during the a.m. peak hour from 90 min to 60 min, which increases the number of trips departing from Wesley Highland Meadows from five (three in one direction and two in the opposite direction) to seven during the a.m. peak hour (which is an additional trip in either direction).

The results of this transit service modification are displayed in Figure 9, which shows overlapping isochrones, in which blue indicates the isochrones under the baseline scenario (with the existing transit service) and red indicates the isochrones under the comparison scenario (with increased frequency/decreased headway). The location of Wesley Highland Meadows is indicated as a blue icon in Figure 9. The red isochrone covers a larger area than the blue isochrone, which means that people from Wesley Highland Meadows can travel farther within an hour under the improved transit network. Specifically, people from Wesley Highland Meadows can reach 6,400 jobs (as opposed to just 135 jobs) within an hour after decreasing the headway of Route 40 from 90 min to 60 min during the a.m. peak hour. The results suggest that a short-term transit service change can substantially improve the transit accessibility from this affordable housing location.

Discussion and Conclusions

In this study, a three-step method for evaluating the transit equity of existing affordable housing units was proposed, with case studies from Nashville, Memphis, and Chattanooga in Tennessee. All these cities have primarily bus-based transit systems. Transit accessibility is not considered in the process of allocating LIHTC for affordable housing planning in Tennessee (*53*). This suggests there may be a need to develop a systematic method for policymakers and practitioners to evaluate the transit accessibility levels of existing affordable housing units.

In Step 1, affordable housing and transit accessibility were visualized. In Step 2a, the results of the Gini coefficient showed that the overall transit accessibility of the combined total of affordable housing units (in the LIHTC, PH, and Multifamily programs) in Memphis and Chattanooga was less equitable than that of the affordable housing units in any single program. The citywide evaluations suggested that transit accessibility levels were distributed less equitably among affordable housing units (a Gini coefficient of 0.895 for the combined total from three housing programs) than randomly selected housing units (with a Gini coefficient of 0.724) in Memphis. The aforementioned findings show that the transit equity of affordable housing units in different cities within a state can vary.

Table 2. Transit Equity Hypothesis Test within 99% Confidence Interval

	Combined affordable housing programs	LIHTC	Multifamily	PH
H_0	$\mu_G = G_{AHs}$	$\mu_G = G_{LIHTC}$	$\mu_G = G_{Multifamily}$	$\mu_G = G_{PH}$
H_1	$\mu_G \neq G_{AHs}$	$\mu_G \neq G_{LIHTC}$	$\mu_G \neq G_{Multifamily}$	$\mu_G \neq G_{PH}$
In Nashville: $\mathbf{n} = 50,\ \bar{x} = 0.833815,\ \sigma = 0.019478$				
t-value	46.689483	-0.425891	145.160974	NA
p-value	<0.00001	0.672052	<0.00001	NA
Result	Reject H_0	Do not reject H_0	Reject H_0	NA
In Memphis: $\mathbf{n} = 50,\ \bar{x} = 0.724131,\ \sigma = 0.015135$				
t-value	-79.028206	19.624625	39.88245	24.89721
p-value	<0.00001	<0.00001	<0.00001	<0.00001
Result	Reject H_0	Reject H_0	Reject H_0	Reject H_0
In Chattanooga: $\mathbf{n} = 50,\ \bar{x} = 0.764597,\ \sigma = 0.032522$				
t-value	10.589294	53.981842	67.671158	65.647894
p-value	<0.00001	<0.00001	<0.00001	<0.00001
Result	Reject H_0	Reject H_0	Reject H_0	Reject H_0

Note: LIHTC = Low-Income Housing Tax Credits; PH = Public Housing.
NA = No Public Housing in Nashville.

Step 2b identified Wesley Highland Meadows in Memphis as an affordable housing location with a high inequity index of 963 because residents at this location could only reach 135 jobs within an hour using transit; however, there is a high potential demand for transit (specifically, 200 affordable housing units at this location). It is important to note that the goal of this step is to compare transit access (supply) and the number of affordable housing units (potential demand) between different existing affordable housing locations to identify those locations with the most inequitable transit access. By identifying these locations and bringing them to the attention of the relevant authorities, planners and policymakers can give greater priority to serving neighborhoods with high levels of affordable housing when making future transit service changes.

In Step 3, a frequency/headway modification (specifically, decreasing the headway of Route 40 from 90 min to 60 min during the a.m. peak hour) was proposed for the Wesley Highland Meadows location. It should be noted that the transit modification evaluated in this study aligns with local planning recommendations in a proposed Transit Vision for the city of Memphis. After modification, the number of jobs accessible via transit to the housing location was shown to increase from 135 to 6,400. The results of the three-step method suggest that short-term transit service changes can improve the transit accessibility of existing affordable housing locations with limited transit access.

This paper contributes to the literature by proposing a three-step method that helps transit agencies and their partners to (a) assess the transit equity of affordable housing programs at the city level, (b) evaluate the transit equity of specific affordable housing locations within a city, and (c) consider possible transit modifications before actual implementation. It is noted that the method relies primarily on open datasets; specifically, GTFS data and geospatial affordable housing locations from HUD make this method widely applicable to other regions of the U.S.A. that have fixed route transit service.

Policy Implications

The three-step method presented in this study provides useful insights for housing authorities and transit agencies that can help guide their efforts toward enhancing transit equity and serving their local communities.

This study offers transit agencies a framework for assessing the equity of transit services for low-income groups, aligning with the Federal Transit Administration's overarching objectives that seek to integrate environmental justice goals into programs, policies, and activities (*66*). By identifying affordable housing locations with higher demand and lower transit supply, transit providers can then prioritize the service to these communities when making transit planning decisions. This approach could help improve transit access for residents in these areas, potentially leading to better mobility and connectivity. The proposed approach may be useful for housing authorities in evaluating the transit accessibility of affordable housing locations at both the citywide and location-specific level, particularly in instances in which transit access is not already incorporated into the federally mandated QAP.

It is important to note that efforts to coordinate transit service planning and affordable housing development are ongoing in many U.S. cities. For example, transit agencies in Raleigh, North Carolina and Austin, Texas each have plans to preemptively acquire land adjacent to

Table 3. The Top Five Inequity Index Affordable Housing Locations in the Three Cities

Inequity index rank	Nashville			Memphis			Chattanooga		
	Affordable housing program	Measures		Affordable housing program	Measures		Affordable housing program	Measures	
1	Terrace Park Townhomes Phase II (LIHTC)	Inequity index	1,496	Greenview Townhomes (LIHTC)	Inequity index	1,092	Silvertree Seniors Apts. (Multifamily)	Inequity index	2,264
		Accessible jobs	258		Accessible jobs	94		Accessible jobs	30
		Housing units	172		Housing units	158		Housing units	124
2	Townhomes of Nashboro Village (LIHTC)	Inequity Index	819	Southwind Lakes Apts. Phase I (LIHTC)	Inequity index	1,057	Cromwell Hills Apts. (PH)	Inequity index	205
		Accessible jobs	200		Accessible jobs	123		Accessible jobs	533
		Housing units	73		Housing units	200		Housing units	200
3	Cobblestone Corners (LIHTC)	Inequity index	680	Wesley Highland Meadows (LIHTC)	Inequity index	963	Eastwood Manor (Multifamily)	Inequity index	123
		Accessible jobs	317		Accessible jobs	135		Accessible jobs	438
		Housing units	96		Housing units	200		Housing units	98
4	Old Hickory Towers (LIHTC)	Inequity index	577	Surrey Apts. I (Multifamily)	Inequity index	709	Orange Grove II (Multifamily)	Inequity index	38
		Accessible jobs	840		Accessible jobs	99		Accessible jobs	457
		Housing units	216		Housing units	108		Housing units	32
5	Heartland Christian Tower (Multifamily)	Inequity index	396	Chapel Place Homes (LIHTC)	Inequity index	331	Walden Group Home (Multifamily)	Inequity index	6
		Accessible jobs	323		Accessible jobs	171		Accessible jobs	850
		Housing units	57		Housing units	87		Housing units	10

Note: LIHTC = Low-Income Housing Tax Credits; PH = Public Housing; Apts. = Apartments.

transit corridors for affordable housing development. Both cities have dedicated funding to minimizing the displacement of existing affordable housing units near new transit developments. The Equitable Development around Transit plan in Raleigh uses zoning around transit stations to encourage the development and preservation of affordable housing units. This type of policy could be considered in other cities to facilitate the coordination of affordable housing and transit services in the future (*67*, *68*).

It is also important to highlight the ongoing efforts of many transit agencies to evaluate transit equity, including those in the case studies evaluated in this paper. For instance, in Nashville, the WeGo transit agency regularly employs the Transit Boardings Estimation and Simulation Tool to assess transit equity for minority and low-income populations, typically as part of the Title VI service equity analysis (*69*). However, WeGo transit planners have noted in a recent survey that the percentage change in access to jobs could serve as a suitable accessibility metric for analyzing the impact of proposed service plans under their Better Bus initiative (*69*). They further expressed a desire to incorporate transit accessibility into their planning activities in collaboration with key community partners in the future (*69*). This study proposes an approach that could be utilized by transit agencies such as WeGo in Nashville for assessing the impact of transit modifications while promoting coordination between transit planning and local partners, particularly housing authorities.

Broadly speaking, it is generally recommended that local transit agencies and housing authorities in the U.S.A. coordinate transit planning and affordable housing development. For example, transit agencies could give priority to affordable housing communities when planning new transit services and/or offer free or discounted fare programs to encourage affordable housing residents to take transit. In addition, housing authorities could consider locating new affordable housing construction in areas with good transit access. Other planning and policy options could also be considered to facilitate housing and transit coordination in the future.

Limitations and Future Research

There are some notable limitations of this study, including the following: the applicability to other areas beyond the U.S.A.; the absence of low-wage jobs in the transit accessibility indicator; the lack of a decay function for job attractiveness; and potential competition between affordable housing residents in the transit accessibility measure.

First, the applicability of the method proposed in this study may be limited to the U.S.A. because housing policies, transit planning practices, and the availability of

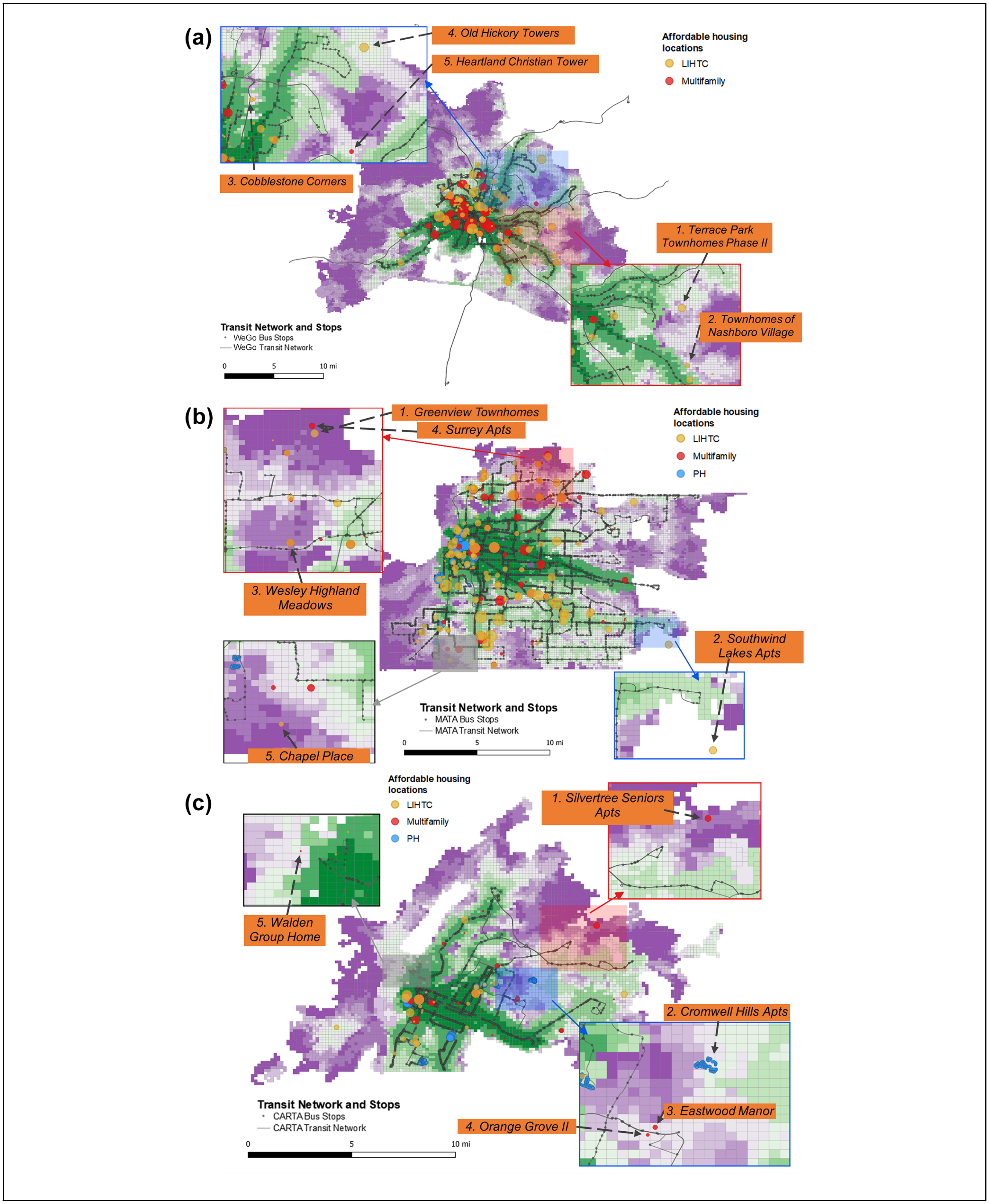

Figure 7. Top five affordable housing locations with limited transit access in three cities: (*a*) Nashville, (*b*) Memphis, and (*c*) Chattanooga.
Note: LIHTC = Low-Income Housing Tax Credits; PH = Public Housing; MATA = Memphis Area Transit Authority; CARTA = Chattanooga Area Regional Transportation Authority; Apts = Apartments.

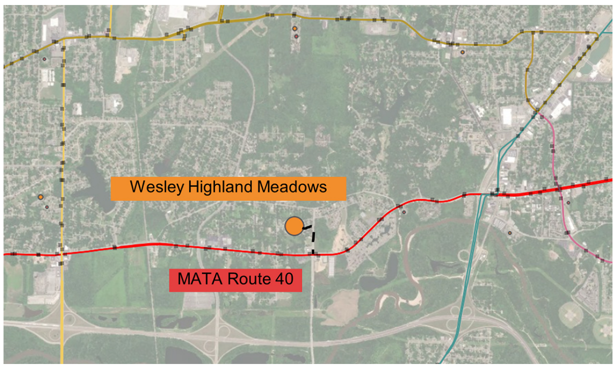

Figure 8. Satellite view of Wesley Highland Meadows and the surrounding road and transit networks.
Note: MATA = Memphis Area Transit Authority.

data vary significantly between different countries. The next two limitations are associated with different factors that can lead to variations in the results of the transit accessibility analysis, potentially influencing the conclusions.

A second limitation relates to the selection of the destinations in the calculation of transit accessibility levels. Some studies suggest that people living in low-income communities are more likely to work in or be qualified only for low-wage jobs (*70–72*). The absence of an analysis of transit accessibility to low-wage job destinations could lead to an underestimation of the transit inequity issues faced by affordable housing units because their residents are typically low-income individuals and may be more likely to be employed in low-wage jobs. The goal of this paper was to provide a general understanding of transit accessibility to all jobs from affordable housing locations; however, future research should consider the unique challenges faced by individuals in low-wage jobs.

Additional limitations pertain to the type of transit accessibility measure used in this study. The use of the cumulative opportunity measure did not consider the decay function of job attractiveness or the potential competition between affordable housing residents and other populations within the same area for available job opportunities. These limitations are particularly noteworthy because previous research on travel behavior has shown that individuals are less likely to travel to jobs that are farther away. Previous research has also suggested that competition for job opportunities may occur among low-income people, with many of them potentially competing for the same position. Consequently, this limitation may result in an underestimation of the transit inequity faced by affordable housing residents. Notably, the conclusions drawn from any study are contingent on the measure of transit accessibility employed, and different measures can potentially yield varying results and implications (*73*, *74*).

There are several areas in which future research could contribute to a deeper understanding of transit equity in affordable housing.

First, although providing access to jobs is an important function of public transit, some travelers, especially low-income populations who may be transit-dependent, rely on transit to get to grocery stores, healthcare facilities, schools, outdoor recreational areas, or other essential services (*72*). Therefore, transit access to other essential services could be a future focus for research.

Second, this paper measured the transit accessibility of fixed route bus service in dense urban areas. However, on-demand services (e.g., dial-a-ride routes) are available in many suburban and rural areas that do not have fixed route service. Therefore, measuring access using on-demand transit services among affordable housing units could be considered in future research.

Third, the proposed method considered the impact of transit service changes on the transit accessibility of a single affordable housing location along the transit route; however, future research could expand the method to consider the impact of transit service changes on all affordable housing locations in the vicinity.

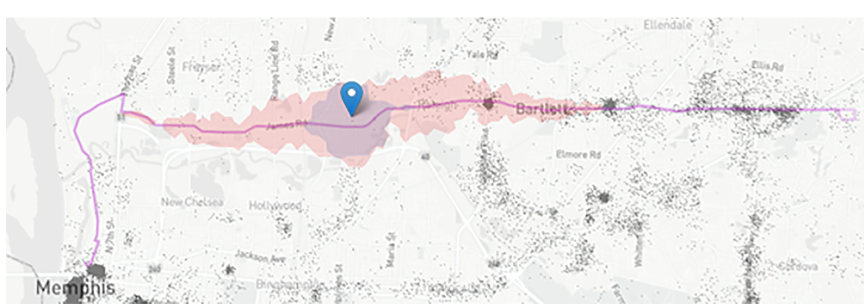

Figure 9. Overlapping isochrones before and after modifying the frequency of MATA transit route 40 for Wesley Highland Meadows.
Note: MATA = Memphis Area Transit Authority.

Fourth, this paper proposed short-term transit modifications for existing affordable housing locations. Future research could consider long-term coordination between transit service planning and affordable housing development (e.g., where to locate new housing developments).

In summary, this study highlights several significant areas for future research. Moreover, the findings offer important policy implications for practitioners seeking to enhance transit equity and potentially improve the accessibility of affordable housing locations. By implementing this methodology, housing authorities and transit agencies can work toward creating more equitable and connected communities.

Acknowledgments

The authors thank the project manager at the Tennessee Department of Transportation, Emily Duchac, for her involvement in this research. The authors would also like to acknowledge the contribution made by Dr. Anson Stewart from Conveyal.

Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: J. Guo, C. Brakewood; data collection: J. Guo, A. Hightower; analysis and interpretation of results: J. Guo, C. Brakewood; draft manuscript preparation: J. Guo, C. Brakewood, A. Hightower, C. Cherry. All authors reviewed the results and approved the final version of the manuscript.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This research was sponsored by the Tennessee Department of Transportation, grant RES2021-08.

ORCID iDs

Jing Guo https://orcid.org/0000-0002-3489-3746
Candace Brakewood https://orcid.org/0000-0003-2769-7808
Ashley Hightower https://orcid.org/0000-0003-2521-4235
Christopher Cherry https://orcid.org/0000-0002-8835-4617

References

1. National Academies of Sciences Engineering and Medicine. *Coordination of Public Transit Services and Investments with Affordable Housing Policies*. National Academies Press, Washington, DC, 2022.
2. Taylor, B. D., and E. A. Morris. Public Transportation Objectives and Rider Demographics: Are Transit's Priorities Poor Public Policy? *Transportation*, Vol. 42, No. 2, 2014, pp. 347–367.
3. Martens, K., J. Bastiaanssen, and K. Lucas. Measuring Transport Equity: Key Components, Framings and Metrics. In *Measuring Transport Equity* (K. Lucas, K. Martens, F. Di Ciommo, and A. Dupont-Kieffer, eds.), Elsevier, Amsterdam, 2019, pp. 13–36.
4. U.S. Bureau of Labor Statistics. *Consumer Expenditures in 2020*, 2021. https://www.bls.gov/opub/reports/consumer-expenditures/2020/home.htm. Accessed June 20, 2022.
5. Kawabata, M., and Q. Shen. Job Accessibility as An Indicator of Auto-oriented Urban Structure: A Comparison of Boston and Los Angeles with Tokyo. *Environment Planning B: Planning Design*, Vol. 33, No. 1, 2006, pp. 115–130.
6. Immergluck, D. Large Redevelopment Initiatives, Housing Values and Gentrification: The Case of the Atlanta Beltline. *Urban Studies*, Vol. 46, No. 8, 2009, pp. 1723–1745.
7. Cervero, R. *Transit-Oriented Development in the United States: Experiences, Challenges, and Prospects*. National Academies Press, Washington, D.C., 2004.
8. Litman, T. *Affordable-Accessible Housing in a Dynamic City: Why and How to Increase Affordable Housing in Accessible Neighborhoods*. Victoria Transport Policy Institute, BC, 2022.
9. Chapple, K., and A. Loukaitou-Sideris. *Transit-Oriented Displacement or Community Dividends? Understanding the Effects of Smarter Growth on Communities*. MIT Press, Cambridge, 2019.
10. Manout, O., P. Bonnel, and L. Bouzouina. Transit Accessibility: A New Definition of Transit Connectors. *Transportation Research Part A: Policy and Practice*, Vol. 113, 2018, pp. 88–100.
11. El-Geneidy, A., D. Levinson, E. Diab, G. Boisjoly, D. Verbich, and C. Loong. The Cost of Equity: Assessing Transit Accessibility and Social Disparity Using Total Travel Cost. *Transportation Research Part A: Policy Practice*, Vol. 91, 2016, pp. 302–316.
12. Welch, T. F. Equity in Transport: The Distribution of Transit Access and Connectivity among Affordable Housing Units. *Transport Policy*, Vol. 30, 2013, pp. 283–293.
13. Stewart, A. F. Mapping Transit Accessibility: Possibilities for Public Participation. *Transportation Research Part A: Policy and Practice*, Vol. 104, 2017, pp. 150–166.
14. Owen, A., and B. Murphy. Access across America: Transit 2019, 2020. http://access.umn.edu/research/america/. Accessed June 12, 2022.
15. Cui, M., and D. Levinson. Primal and Dual Access. *Geographical Analysis*, Vol. 52, No. 3, 2020, pp. 452–474.
16. Levinson, D., and D. King. *Transport Access Manual: A Guide for Measuring Connection between People and Places*. Committee of the Transport Access Manual, University of Sydney, Sydney, 2020.
17. Zuo, T., H. Wei, and N. Chen. Promote Transit via Hardening First-and-Last-Mile Accessibility: Learned from Modeling Commuters' Transit Use. *Transportation Research Part D: Transport and Environment*, Vol. 86, 2020, article 102446.
18. El-Geneidy, A. M., and D. M. Levinson. *Access to Destinations: Development of Accessibility Measures*. Minnesota

Department of Transportation Office of Research Services, St. Paul, MN, 2006.
19. Blanchard, S. D., and P. Waddell. Urbanaccess: Generalized Methodology for Measuring Regional Accessibility with an Integrated Pedestrian and Transit Network. *Transportation Research Record*, 2017. 2653: 35–44.
20. El-Geneidy, A., and D. Levinson. Making Accessibility Work in Practice. *Transport Reviews*, Vol. 42, No. 2, 2022, pp. 129–133.
21. Grengs, J. Job Accessibility and the Modal Mismatch in Detroit. *Journal of Transport Geography*, Vol. 18, 2010, pp. 42–54.
22. Palacios, M. S., and A. El-Geneidy. Cumulative versus Gravity-Based Accessibility Measures: Which One to Use? *Findings*, February 11, 2022. https://findingspress.org/article/32444-cumulative-versus-gravity-based-accessibility-measures-which-one-to-use. Accessed June 12, 2023.
23. Shen, Q. Location Characteristics of Inner-City Neighborhoods and Employment Accessibility of Low-Wage Workers. *Environment Planning B: Planning Design*, Vol. 25, No. 3, 1998, pp. 345–365.
24. Kawabata, M., and Q. Shen. Commuting Inequality between Cars and Public Transit: The Case of the San Francisco Bay Area, 1990–2000. *Urban Studies*, Vol. 44, No. 9, 2007, pp. 1759–1780.
25. Merlin, L. A., and L. Hu. Does Competition Matter in Measures of Job Accessibility? Explaining Employment in Los Angeles. *Journal of Transport Geography*, Vol. 64, 2017, pp. 77–88.
26. Allen, J., and S. Farber. A Measure of Competitive Access to Destinations for Comparing across Multiple Study Regions. *Geographical Analysis*, Vol. 52, No. 1, 2020, pp. 69–86.
27. Farber, S., M. Z. Morang, and M. J. Widener. Temporal Variability in Transit-Based Accessibility to Supermarkets. *Applied Geography*, Vol. 53, 2014, pp. 149–159.
28. Ghorbanzadeh, M., K. Kim, E. E. Ozguven, and M. W. Horner. A Comparative Analysis of Transportation-Based Accessibility to Mental Health Services. *Transportation Research Part D: Transport and Environment*, Vol. 81, 2020, article 102278.
29. Conway, M. W., A. Byrd, and M. van der Linden. Evidence-Based Transit and Land Use Sketch Planning Using Interactive Accessibility Methods on Combined Schedule and Headway-Based Networks. *Transportation Research Record*, 2017. 2653: 45–53.
30. Ricciardi, A. M., J. Xia, and G. Currie. Exploring Public Transport Equity between Separate Disadvantaged Cohorts: A Case Study in Perth, Australia. *Journal of Transport Geography*, Vol. 43, 2015, pp. 111–122.
31. Delbosc, A., and G. Currie. Using Lorenz Curves to Assess Public Transport Equity. *Journal of Transport Geography*, Vol. 19, No. 6, 2011, pp. 1252–1259.
32. Aman, J. J. C., and J. Smith-Colin. Transit Deserts: Equity Analysis of Public Transit Accessibility. *Journal of Transport Geography*, Vol. 89, 2020, article 102869.
33. Litman, T. *Evaluating Transportation Equity*. Victoria Transport Policy Institute, BC, 2017.
34. Manaugh, K., M. G. Badami, and A. M. El-Geneidy. Integrating Social Equity into Urban Transportation Planning: A Critical Evaluation of Equity Objectives and Measures in Transportation Plans in North America. *Transport Policy*, Vol. 37, 2015, pp. 167–176.
35. Sharma, I., S. Mishra, M. M. Golias, T. F. Welch, and C. R. Cherry. Equity of Transit Connectivity in Tennessee Cities. *Journal of Transport Geography*, Vol. 86, 2020, article 102750.
36. Gini C. Variabilità e mutabilità: contributo allo studio delle distribuzioni e delle relazioni statistiche. [Fasc. I.]. Tipogr. di P. Cuppini, 1912.
37. Kaplan, S., D. Popoks, C. G. Prato, and A. Ceder. Using Connectivity for Measuring Equity in Transit Provision. *Journal of Transport Geography*, Vol. 37, 2014, pp. 82–92.
38. Chen, Z., Y. Guo, A. L. Stuart, Y. Zhang, and X. Li. Exploring the Equity Performance of Bike-Sharing Systems with Disaggregated Data: A Story of Southern Tampa. *Transportation Research Part A: Policy and Practice*, Vol. 130, 2019, pp. 529–545.
39. U.S. Department of Housing and Urban Development. Low-Income Housing Tax Credit (LIHTC). https://www.huduser.gov/portal/datasets/lihtc.html. Accessed June 22, 2022.
40. U.S. Department of Housing and Urban Development. *Multifamily Housing* 2022. https://www.hud.gov/program_offices/housing/mfh. Accessed June 22, 2022.
41. U.S. Department of Housing and Urban Development. *Public Housing* 2022. https://www.hud.gov/program_offices/public_indian_housing/programs/ph/. Accessed June 22, 2022.
42. Preston, G., and V. J. Reina. Sheltered from Eviction? A Framework for Understanding the Relationship between Subsidized Housing Programs and Eviction. *Housing Policy Debate*, Vol. 31, No. 3–5, 2021, pp. 785–817.
43. U.S. Department of Housing and Urban Development. *Geospatial Data Storefront* 2020. https://hudgis-hud.opendata.arcgis.com/. Accessed June 22, 2022.
44. Gramlich, E. Qualified Allocation Plan: National Low Income Housing Coalition, 2014https://nlihc.org/sites/default/files/2014AG-259.pdf.
45. Johnson, M. S. *Poverty Deconcentration Priorities in Low-Income Housing Policy: A Content Analysis of Low-Income Housing Tax Credit (LIHTC) Qualified Allocation Plans*. Virginia Commonwealth University, Richmond, VA, 2014.
46. Pendall, R., A. C. Nelson, C. J. Dawkins, and G. J. Knaap. . Connecting Smart Growth, Housing Affordability, and Racial Equity. In *The Geography of Opportunity: Race and Housing Choice in Metropolitan America* (X. de Souza Briggs, ed.), Brookings Institution Press, Washington, DC, 2006, pp. 219–246.
47. Palm, M., and D. Niemeier. Does Placing Affordable Housing near Rail Raise Development Costs? Evidence from California's Four Largest Metropolitan Planning Organizations. *Housing Policy Debate*, Vol. 28, No. 2, 2018, pp. 180–198.
48. Liu, D., M. P. Kwan, Z. Kan, and Y. Song. An Integrated Analysis of Housing and Transit Affordability in the Chicago Metropolitan Area. *The Geographical Journal*, Vol. 187, No. 2, 2021, pp. 110–126.
49. Duncan, M. The Impact of Transit-Oriented Development on Housing Prices in San Diego, CA. *Urban Studies*, Vol. 48, No. 1, 2011, pp. 101–127.

50. Houston, D., V. Basolo, and D. Yang. Walkability, Transit Access, and Traffic Exposure for Low-Income Residents with Subsidized Housing. *American Journal of Public Health*, Vol. 103, No. 4, 2013, pp. 673–678.
51. Park, H. J., and K. Choi. Affordable Housing Program Tenants and Their Access to Public Transportation and Employment. *Journal of Housing the Built Environment*, Vol. 36, No. 3, 2021, pp. 1119–1139.
52. U.S. Census Bureau. 2019 Census, 2019. https://data.census.gov/table. Accessed January 31, 2023.
53. Perrey, R. M. Low-Income Housing Credit 2022 Qualified Allocation Plan: Tennessee Housing Development Agency, 2022. https://www.novoco.com/sites/default/files/atoms/files/tennessee-lihtc-qap-final-2022-amended-02172022.pdf
54. Bureau USC. Population and Housing Unit Estimates Tables 2021. https://www.census.gov/programs-surveys/popest/data/tables.html. Accessed October 9, 2022.
55. Lambe, W., and M. de Zeeuw. *The Small Cities Study Tour: Chattanooga's Comeback*. Federal Reserve Bank of Atlanta, GA, 2016.
56. Federal Bureau of Investigation. 2019 Crime in the United States, 2019. https://ucr.fbi.gov/crime-in-the-u.s/2019/crime-in-the-u.s.-2019/topic-pages/tables/table-6. Accessed October 9, 2022.
57. Bertolaccini, K. An Analysis of Changes to Transit Accessibility and Equity after the Opening of A Bus Rapid Transit System in Hartford, Connecticut. *Journal of Transport Land Use*, Vol. 11, No. 1, 2018, pp. 1163–1171.
58. Fransen, K., T. Neutens, S. Farber, P. De Maeyer, G. Deruyter, and F. Witlox. Identifying Public Transport Gaps Using Time-Dependent Accessibility Levels. *Journal of Transport Geography*, Vol. 48, 2015, pp. 176–187.
59. Bok, J., and Y. Kwon. Comparable Measures of Accessibility to Public Transport Using the General Transit Feed Specification. *Sustainability*, Vol. 8, No. 3, 2016, pp. 224–236.
60. U.S. Census Bureau. 2020 Census, 2020. https://www.census.gov/programs-surveys/decennial-census/decade/2020/2020-census-main.html. Accessed May 20, 2022.
61. Conway, M. W., and A. F. Stewart. Getting Charlie off the MTA: A Multiobjective Optimization Method to Account for Cost Constraints in Public Transit Accessibility Metrics. *International Journal of Geographical Information Science*, Vol. 33, No. 9, 2019, pp. 1759–1787.
62. Brown, M. C. Using Gini-Style Indices to Evaluate the Spatial Patterns of Health Practitioners: Theoretical Considerations and an Application Based on Alberta Data. *Social Science & Medicine*, Vol. 38, No. 9, 1994, pp. 1243–1256.
63. U.S. Census Bureau. *Housing Units* 2022. https://www.census.gov/quickfacts/fact/note/US/HSG010221. Accessed June 30, 2022.
64. Conveyal User Manual. Modification types 2022. https://docs.conveyal.com/edit-scenario/modifications. Accessed June 22, 2022.
65. City of Memphis. The Future of Transit in the City of Memphis 2022. https://transitvision.memphistn.gov/. Accessed June 22, 2022.
66. FTA. *Circular FTA C 4702.1 B: Title VI Requirements and Guidelines for Federal Transit Administration Recipients*. U.S. Department of Transportation Washington, D.C., 2012.
67. City of Austin. Anti-Displacement Funding 2020. https://www.austintexas.gov/page/anti-displacement-funding. Accessed June 29, 2022.
68. City of Raleigh. Equitable Transit-Oriented Development Guidebook 2020. https://cityofraleigh0drupal.blob.core.usgovcloudapi.net/drupal-prod/COR22/EDATGuidebook.pdf
69. National Academies of Sciences Engineering and Medicine. *Assessing Equity and Identifying Impacts Associated with Bus Network Redesigns*. National Academies Press, Washington, DC, 2022.
70. Delmelle, E., I. Nilsson, and P. Adu. Poverty Suburbanization, Job Accessibility, and Employment Outcomes. *Social Inclusion*, Vol. 9, No. 2, 2021, pp. 166–178.
71. Benner, C., and A. Karner. Low-Wage Jobs-Housing Fit: Identifying Locations of Affordable Housing Shortages. *Urban Geography*, Vol. 37, No. 6, 2016, pp. 883–903.
72. Klumpenhouwer, W., and W. Huang. A Flexible Framework for Measuring Accessibility with Destination Bundling. *Journal of Transport Geography*, Vol. 91, 2021, article 102949.
73. Giannotti, M., D. B. Tomasiello, and T. A. Bittencourt. The Bias in Estimating Accessibility Inequalities Using Gravity-Based Metrics. *Journal of Transport Geography*, Vol. 101, 2022, article 103337.
74. Tiznado-Aitken, I., J. C. Muñoz, and R. Hurtubia. Public Transport Accessibility Accounting for Level of Service and Competition for Urban Opportunities: An Equity Analysis for Education in Santiago de Chile. *Journal of Transport Geography*, Vol. 90, 2021, article 102919.