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Equity in transport: The distribution of transit access and connectivity among affordable housing units

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ABSTRACT

In the United States, federal agencies are required to work towards providing equal access to resources for minority and low-income populations. Access to quality public transportation is critical for mobility to many of these populations. Determining how transit service is distributed among vulnerable groups has the potential to significantly enhance policy analysis. While many measures of accessibility exist, due to the complexity of transit networks and the scale of the urban areas, limited research has been conducted on developing a tool to measure how equitable the distribution of transit access is in a region. This paper develops a comprehensive method to quantify the quality of service and accessibility at each transit node in a network, combined with an index to measure the inequity (concentration of quality service) at the micro scale. These measures are applied to the distribution of all residential housing units, a random sampling of units and U.S. Department of Housing and Urban Development subsidized units in Baltimore, Maryland; to determine if the subsidized housing programs are achieving major policy objectives of providing equitable transit access to vulnerable groups. The results show that transit connectivity and accessibility is distributed among some types of subsidized housing units more equitably than can be achieved by random sampling in the general population, but for other types, the distribution is less equitable; indicating some policies to enhance transit access among these units have not been effective. Evidence from this study suggests that developers of affordable housing and transportation planners should work together to find development locations that place more emphasis on transit locations with high connectivity rather than simply reducing distance to any transit.

1. Introduction

One of the most important roles that public transit serves is bridging the mobility gap between captive and choice riders. To adequately work in this capacity, groups that lack private transportation must have access to high quality transit service. For many urban residents, transit operates as their only conduit to employment opportunities (Blumenberg and Ong, 2001). A lack of access to good quality transit for these individuals can result in low employment participation and long-term cycles of poverty (Sanchez, 1999, 2004). To ensure members of vulnerable groups have equal opportunities to employment, services and goods; tools are needed to measure the distribution of transit service among the population. Such a measures exists in the equity literature, but they are infrequently applied to the transportation and housing fields.

For the last several decades it has been the goal of the US federal government to decentralize concentrations of poverty, brought on in part by past housing policies. This effort began in the 1970s with the development of a voucher program. The program, called Section 8, placed less focus on the production of affordable housing and allowed low-income residents to more freely select their residential location. A decade later congress instituted the Low Income Housing Tax Credit (LIHTC) program that offered tax breaks to developers of affordable housing. The aim of the LIHTC program was to once again encourage the production of low-income housing. Both programs, which fall under the purview of the U.S. federal Department of Housing and Urban Development (HUD), are embedded with various goals and mandates to ensure participants of each program have access to economic, social and recreational opportunities. This study examines how well these programs spatially match low-income residents with high quality public transportation access. To conduct the analysis this, a spatial distribution equity analysis tool called the Gini index is paired with a comprehensive index of transit connectivity and accessibility.

The remainder of this paper is organized into five sections. The first section presents a review of the literature followed but a description of the methodological framework developed to analyze the issue of transit connectivity, access and equity. The third section

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describes the case study area. Results of the method application are presented in the fourth section followed by conclusions, policy implications and suggestions for further research in the fifth section.

2. Literature review

There is a rich literature examining issues of equity, housing subsidies and transit service. To better deal with this complex body of literature, the review is composed of four parts. The first section offers a discussion on the general terms of equity and its use in policy. The second section covers transportation equity specifically, followed by a discussion of subsidized housing equity. The final section discusses traditional measures of transit service.

2.1. Equity

Equity issues have been examined in the literature under a variety of disciplines. A primary focus has been on the distribution of services around a region or among a population. For instance, in geography to examine the accessibility or economic activity (Keeble et al., 1982) or the distribution of particular services (Truelove, 1993). In medicine to measure the segmentation of population and its implications on healthcare services (Bloom, 2001) and the location of health care facilities among the population (Rosero-Bixby, 2004). Beckett and Koenig (2005) apply equity to the field of sociology in general, while Kokko et al. (1999) assess how equal the application of such measures have been in the literature. In economics, Atkinson (1975) formulates the classic application of equity to income distribution, and in political science it has commonly been used for welfare analysis (Maniquet and Sprumont, 2005).

Another important area of equity analysis that has received much less attention in the literature is the match between the distribution of services and the need for those services. Allard (2008) examines the distribution of social safety-net services in several cities among high and low poverty groups. The analysis reveals that accessibility to services is critical for individuals, with a service catchment area of 3 mile. However Allard also finds evidence that neighborhoods with higher poverty rates have much less access to assistance than neighborhoods with lower rates of poverty. The findings echo others that have discovered a mismatch between individual need and location of services. Grønbjerg and Paarlberg (2001) found that counties with higher poverty rates had access to fewer non-profits per capita than lower poverty counties. Archibald and Putnam Rankin (2013) in a study of 3141 US counties concluded that locations with the greatest social need often had much worse access to health care services.

Equity is divided into two types, horizontal and Vertical (Berliant and Strauss, 1985; Kakwani, 1984; Repetti and McDaniel, 1993). Horizontal equity is concerned with the proportional distribution of an attribute among similar members of a population. Vertical equity focuses on the distribution of an attribute among specific groups (Mooney, 1996). The two types of equity are much different in scope. Where vertical equity requires that different groups receive different amounts of a benefit, horizontal equity requires that within each group of similar individuals, a similar benefit be received. More broadly and in the context of transit service provision, the two types of equity work together to emphasize that transit dependent groups should have access to equal amounts of quality transit (horizontal equity) and those in society most dependent on transit in should receive more access to transit service (vertical equity) (Culyer, 2001). The concept is applied in this paper, first to measure how much transit service access low-income households have compared to the rest of the population (vertical equity) and whether transit service access is evenly distributed among low-income households receiving a variety of subsidized housing benefits (horizontal equity).

Many studies on the broader subject of vertical equity fall into a category of equity called Environmental Justice (EJ) (Bowen et al., 1995). EJ is generally referred to as the fair involvement of low income and minority groups in a process, or assurance of equal access to equal resources for all members of the class (Capek, 1993). The ideals of EJ have been considered important at the top levels of government. In 1994 president Clinton signed Executive Order 12898, mandating:

> Each Federal agency shall make achieving environmental justice part of its mission by identifying and addressing, as appropriate, disproportionately high and adverse human health or environmental effects of its programs, policies, and activities on minority populations and low-income populations.

It is within the framework of EJ that the distribution of transportation access to certain groups can be analyzed.

2.2. Transportation equity

There is a strong need for transit, especially for many vulnerable groups. Income is closely related to transit need. Many studies have found a direct and positive relationship between vehicle ownership and rising income, that is, as household income increases so do the number of vehicles owned by a household (Dargay and Gately, 1999). The inverse of this relationship has also been found, such that a reduction in household income leads to a reduction in vehicle ownership (Dargay, 2001). Paulley et al. (2006) find evidence that vehicle ownership is directly related to the demand for public transportation; the inference being that lower income families own fewer vehicles and are more reliant on public transport. Berube and Raphael (2005) find that 20% of low income households do not own a single personal vehicle, a rate that increases in urban areas with high poverty rates. Ong (1996) finds a high rate of welfare recipients lack a personal vehicle, but argues that assisting with vehicle ownership may provide the best opportunity for employment. However, there appears to be evidence that many low-income households attempt to locate near transit, where it is available. Murphy (2010) in a recent study of US Transit Oriented Developments found that nearly 50% of residents that live "[w]ithin a half mile of existing rail stations… make less than $25,000 a year. Within a quarter mile of existing rail stations, renters make up 65% of the population." Given low-income households' lack of vehicle ownership, particularly in high poverty urban areas, the apparent desire to locate near transit access points and the availability of transit in many large urban areas (like Baltimore City), it would be beneficial for subsidized housing policy to direct development such that the distribution of quality transit service benefits low income households.

The distribution of access to transportation among individuals of differing economic wealth is an issue closely related to Environmental Justice. The US department of transportation (DOT) defines what constitutes EJ in the context of transportation in three parts. First "to avoid, minimize, or mitigate disproportionately high and adverse human health and environmental effects, including social and economic effects, on minority populations and low-income populations." Second, "to ensure the full and fair participation by all potentially affected communities in the transportation decision-making process." Third, "to prevent the denial of, reduction in, or significant delay in the receipt of benefits by minority and low-income populations" (USDOT, 1997). The third point in this list is the one most closely related to the goals of EJ. With this directive, the USDOT has worked with many other federal agencies to enhance the distribution of access to opportunities through transportation.

Even with the EJ directives in effect, studies show mixed evidence on the distribution of transit among low-income residents. A recent report appraising transit access for the Section 811 program (subsidized housing for the disabled) by the National Housing Trust and American Association of Retired Persons (AARP) found that 64% of all federally subsidized housing units in the US are within a half mile of transit access. The number rises to 74% in the city of Baltimore, the study area for this paper (Murphy, 2010). Foth et al. (2013) examined the distribution of transit accessibility to socially disadvantaged groups in Toronto, finding census tracts with higher rates of social disadvantage had better transit accessibility and lower travel times compared to other parts of the region. However, many more studies find considerable spatial mismatch between residential and job location; with very little transportation access to bridge the space (Hess, 2005; Horner and Mefford, 2007; Ong and Miller, 2005). Delbosc and Currie (2011) measured equity as it relates to the distribution of transit service frequency in Melbourne Australia. The results show an overall Gini coefficient of .68, indicating that roughly 70% of the population shares just 19% of the transit service. Delmelle and Casas (2012) measure the distribution of transit access among different population groups in Cali, Colombia; finding the addition of a BRT trunk line increased the equitable distribution of access to services. Bureau and Glachant (2011) measured the distributional effects of changes in transit fares and speed, finding fare reductions result in the greatest transit equity for low income groups in Paris.

Just as the there is considerable debate about the distribution of transportation among low-income households, there is an equally diverse discussion about the best policy options to bridge such spatial mismatch where it exists. A number of scholars contend that providing better access to personal vehicles presents the best opportunity for low-income households. For welfare recipients, a personal vehicle provides the opportunity for better access to employment (Ong and Miller, 2005; Ong, 2002). Other scholars advocate for housing policy that brings low-income households closer to employment (Ihlanfeldt and Sjoquist, 1998; Minocha et al., 2008), while some urge a mix of better public transit and vehicle access (Hess, 2005). From a housing and public transportation policy prospective, HUD and transit agencies are more interested in moving housing closer to transit as a means of bridging the residential and employment location gap.

2.3. HUD and equity

The US Department of Housing and Urban Development, as a federal entity must comply the executive order requiring EJ achievements. To this end, HUD has worked to encourage subsidized housing units located near transit access. The largest subsidized housing program in the U.S. is the Section 8 program. The program provides vouchers to low-income households to cover the difference in cost between the fair market value of a private market unit and 30% of the family's adjusted income. Households with an income up to 80% of area median income qualify for the program (Schwartz, 2010). The Section 8 program is a unique departure from traditional U.S. subsidized housing policy in that it does not directly work towards the construction of new housing units, but attempts to disperse low income households into a range of existing market rate units (Galster et al., 1999).

The Low Income Housing Tax Credit Program (LIHTC) program is an indirect subsidy program that offers developers and property owners tax credits for affordable rental housing development. The program offers a dollar for dollar match between tax credits received and reductions in federal income taxes for 10 years. Developers are able to sell federal tax credits, typically through an intermediary called a syndicator in exchange for equity financing (Desai et al., 2010). The framework for this program allows the federal government to allocate credits directly to states to be used at their discretion, based on the state's population, up to about $2 per capita. The program has been hugely popular as it has been used to develop nearly 16% all multifamily homes since the program's inception nearly 30 years ago under the Tax Reform Act of 1986 (Schwartz, 2010). The LIHTC has also become the de-facto federal low-income housing production program (Cummings and DiPasquale, 1999). It has produced so many affordable rental units, that it approaches scales of available units comparable to the Section 8 voucher program (O'Regan and Horn, 2013). In Maryland the program accounts for over 22% of all multifamily homes constructed in the same period (Danter Company, n.d.).

The allocation process allows states to set their own requirements for qualifying projects so long as they meet a federal minimum standard. Many states set requirements that are far more strict than the federal rules (Desai et al., 2010). One of the goals of the program is to encourage rental developments in proximity to transit. Approximately 31 states offer point-based incentives to the project selection criteria based on proximity to transit of the development. In Maryland, points are awarded for development that occurs in “transit oriented developments” (TODs). TODs are defined as “having a density that exceeds 25 units per acre, involves mixed use or is part of a larger mixed use undertaking, involves good non-motorized transport design (walkability), and (a) is located within 0.5 mile of a mass or public transit or rail station, or (b) is located within 0.25 mile of a bus depot or bus stop with scheduled service at intervals at most 30 min between the hours of 6:30 am and 7:00 pm” (DHCD, n.d.). This criteria is extremely broad and may easily encourage developments with widely differing transit access. While the criteria for a TOD is adequate, not all rail stations provide the same opportunities to patrons to access important destinations; nor are rail stations easily comparable with the access provided by bus. Further, the points awarded for development in a TOD are quite small. Of the 315 points awarded for potential developments only 5 points are awarded for TOD locations. Considering the criteria for development in a TOD, the points do not likely match the substantial added cost for development in such an area.

There is considerable debate between advocates of directly subsidized housing (Section 8) and indirect subsidies (LIHTC). A primary concern is whether either of these programs is furthering the federal housing policy goal to deconcentrate poverty. As Galster (1997) frames the two policies, Section 8 focuses on the demand-side, offering vouchers to individuals. The LIHTC program falls on the supply side, seeking an increase in the stock of affordable housing. Proponents of the demand side programs, argue that directly subsidizing housing better addresses the current need for affordable housing and may in the long-run may indirectly increase the number of affordable units (Galster, 1997). Deng (2007) argues that in some instances voucher programs perform better at helping residents escape high-poverty locations. Supply-side proponents argue that increasing the affordable housing stock is a way to ensure higher quality living standards among affordable units and helps reduce the market cost of rental units in general (Apgar, 1990). Other studies find programs like Section 8 have led to substantial increases in the overall cost of rent (Susin, 2002) and in some cases may lead to increased concentrations of poverty (Guhathakurta and Mushkatel, 2000). While this study does not wade into the merits of the supply and demand side debate, the analysis does provide insight into how each program has placed residents in proximity to quality transit service.

2.4. Transit service quality measures

Despite the importance of transit service, accessibility and equity in federal policy, the treatment of such measures in the literature is often simplistic. It is common for Transit service indicators to measure service quality in terms of the number of routes in an area or frequencies at specific stops (Bowman and Turnquist, 1981; Sanchez et al., 2004). Accessibility is frequently measured by walk time proximity (Handy and Niemeier, 1997), though many more accessibility measures exist that incorporate land use, temporal and individual characteristics (Geurs and Van Wee, 2004). Little has been done to measure policy performance in the context of access to opportunities at destinations, scaled by transit service quality, travel distance and time, transfers and walk time. These more advanced measure are critical in transit service. While the proximity to a transit stop is important, it says little about the scale and ease of access the stop offers passengers to participate in regional activities. Other measures of quality take a subjective approach to service provision, qualifying state preferences (Hensher et al., 2003) or passenger perceptions (Eboli and Mazzulla, 2011). Though these measure are important from a passenger perspective, they require substantial and costly data inputs to estimate. In order to measure and compare service distribution for policy analysis, an objective and relatively to calculate (i.e. low data requirements and straight forward mathematics) is required.

This paper takes on the question of whether HUD's subsidized housing programs, with the aim of increasing transit service quality and accessibility among all affordable housing residents, works in the way the program intends. The question is answered through comparisons of equity index results for the entire population of housing stock, random samples of units and for subsidized housing in the city of Baltimore.

3. Methodology

This section describes the methodology for measuring transit service connectivity and equity. In the first part the method for calculating transit connectivity is described. The second part develops a distance decay function to measure accessibility, and in the third part, connectivity is used as the basis to measure transit equity with Lorenz curves and the Gini Index.

3.1. Connectivity

A common treatment of transit connectivity or service level in the literature is transit frequency at a stop. This formulation does not provide valuable information about the opportunities accessible by transit, the time it takes to reach those opportunities, or the ability to transfer to different routes and modes to reach a broader array of activities. This information is critical in determining the true quality of transit provision at a given stop. To address these shortcomings, this paper adopts a more comprehensive connectivity measure, first developed by Mishra et al. (2012). The measure uses frequency, speed, distance, capacity, required transfers and activity density of the underlying land use served by a transit node, for all modes including buses, light rail, bus rapid transit, and other similar transit facilities.

The connecting power of a transit line is a function of the inbound and outbound powers, as the connecting power may vary depending on the direction of travel (Eqs. (1) and (2)). The inbound and outbound connecting power of a transit line can be defined as follows.

$$P^o_{l,n} = \alpha\left(C_l \times \frac{60}{F_l} \times H_l\right) \times \beta V_l \times \gamma D^o_{l,n} \times \vartheta A_{l,n} \times \varphi T_{l,n} \quad (1)$$

$$P^i_{l,n} = \alpha\left(C_l \times \frac{60}{F_l} \times H_l\right) \times \beta V_l \times \gamma D^o_{l,n} \times \vartheta A_{l,n} \times \varphi T_{l,n} \quad (2)$$

where, C_l is the average vehicle capacity of line l, F_l is the frequency on line l (60 is divided by F_l to determine the number of operations per hour), H is the daily hours of operation of line l, V_l is the speed of line l, and $D^o_{l,n}$ is the distance of line l from node n to the destination. The parameter α is the scaling factor coefficient for capacity which is the reciprocal of the average capacity of the system multiplied by the average number of daily operations of each line. β is the scaling factor coefficient for speed represented by the reciprocal of the average speed on each line, and γ is the scaling factor coefficient for distance which is the reciprocal of the average network route distance.

The quantity of opportunities accessible at each node in the system is incorporated into the index with Eq. (3). The density measurement A represents the development pattern based on both land use and transportation characteristics. The literature defines the level of development a number of ways, but for simplification purposes it is calculated here as the ratio of households and employment in a zone to the area of the zone. Mathematically, activity density is defined as:

$$A_{l,n} = \frac{H^z_{l,n} + E^z_{l,n}}{\Theta^z_{l,n}} \quad (3)$$

where, $H^z_{l,n}$ is the number of households in zone z, $E^z_{l,n}$ is the number of jobs and $\Theta^z_{l,n}$ is the area of zone z.

The connectivity index measures the aggregate connecting power of all lines that are accessible to a given node. The index scores are scaled based on the quality of individual lines that are incident upon the node (Eq. (4)). This equation adds the number to transit lines "l" at node "n", and φ is the scaling factor for the number of transit lines. The transfer scale is simply the sum of the connectivity index scores for each of the transit lines that cross a node divided by the count of the number of lines that are incident upon the node. The transfer scaled index is defined as:

$$\frac{T_{l,n} = \sum P^t_{l,n}}{\Theta^n_l} \quad (4)$$

where, $p^z_{l,n}$ is the connecting power of transit line that cross a node, $\Theta^z_{l,n}$ is the number of transit lines that serve the node. The transfers scale is used as a factor to make stops with access to multiple transit lines comparable. A stop with two highly connected transit lines is not the same as a stop with access to a half dozen poorly connected transit lines. The scaling factor therefore preserves the connectivity score of the stop with a couple well connected lines and penalizes the connectivity score of the stop with multiple poorly connected lines.

3.2. Transit catchment and accessibility

This paper seeks to measure the distribution of transit access among the population, compared to specific groups within the population. To determine accessibility to stops near a household for inclusion into the connectivity index, we define a half-mile catchment around each housing unit. However, the distance from the housing unit to the transit stop is important. A stop located half a mile from the zone provides less connectivity than a zone that is located just a tenth of a mile away. A distance decay function is used to pro-rate the connectivity of transit nodes within a half-mile of each unit based on its distance from the centroid of the residential parcel. This study examines walking distance from all household (nearly 250,000) parcels in Baltimore City to all transit stops. To expedite the computing process, the analysis is limited to Euclidian or straight-line distance between these points rather than network distance.

Eq. (5) represents the connectivity calculation for a station within the half-mile catchment area. $\rho_{z_1,n}$ is the pro-rated connectivity and is defined as

$$\rho_{h_1,n} = a \times exp^{-bt_{h_1,n}} \quad (5)$$

where, a and b are the parameters of pro-rated connectivity and $t_{h_1,n}$ is the walk time to travel from housing unit h_1 to transit stop n. The parameters for a and b are from Kim et al. (2005) and estimated based on empirical data.

Fig. 1 provides a simple example of the half-mile catchment areas and the calculation of the prorated connectivity. In this case, the Y value is used to reduce the connectivity of each node. Transit nodes that are outside the catchment area have a Y value of 0.

The sum of the connecting power of each node in the catchment area is scaled by the number of nodes within the catchment area of each housing unit. Thus, a housing unit in a very dense transit area is made comparable to a housing unit in a less dense area. Eq. (6) shows the connectivity index of a housing unit

$$\theta_{hu} = (|S_\omega| - 1)^{-1} \sum P^t_{l.n}(\rho_{n_1,n}) \quad (6)$$

where S_ω us the number of stops accessible to the housing unit. This service quality index improves upon others, in that it uses not just measure service supply but also the quality of access provided to all destinations. This measure represents a significant improvement over many service indexes while maintaining tractability and practicality. There are however, a few limits to the measure as it is applied in this paper. The current methodology treats each household unit and job as homogenous within the activity system; that is, the activity and accessibility indicator increases with each additional job accessible from the transit stop rather than separating out types of employment and household attributes. Though this does not significantly impact the measurement of transit quality distribution it may provide an additional amount of information for policymakers if employed in future research.

3.3. Inequality index

Inequity is a measure of geographic concentration of a certain phenomenon. A common use of such an index is the distribution of income among populations. For instance, many studies look at the cumulative proportion of the population of a county (or among counties) and determine the cumulative proportion of income held at each level. The most common measure for this inequity is the Gini index. The index measures the difference between a perfect equity line (a straight line, where in the above example, 0% of income is held by 0% of the population, 50% of income is held by 50% of the population and 100% of the income is held by 100% of the population), and a Lorenz curve which measures the real income distribution (Marshall and Olkin, 1979). When there is no difference between the perfect equity line and the Lorenz curve, the index value is 1, representing perfect equity. The index ranges from a value of 0 for perfect inequity to 1.

The same principle can be applied to the distribution of quality transit service. In this case it becomes the cumulative proportion of population and the cumulative proportion of transit connectivity immediately accessible to that population. The resulting Gini index values allow the distributions of transit access to be compared across a variety of locations.

In Fig. 2 a graph of the perfect equity line and a sample Lorenz curve is shown. The 45-degree angle is the perfect equity line, showing an equal distribution of a cumulative attribute among the population. The area below the equity line is the Lorenz curve, which represents the level of inequity. The Gini index is essentially the ratio of the dark shaded area (between the two curves) to the whole shaded area.

Finding the difference between Lorenz curves and calculating the resulting Gini index is a mathematically complex task, which can be solved by integration. However, the difference between the two curves can be approximated based on the difference between each interval using the following formula (Brown, 1994):

$$G_\alpha = 1 - \sum_{k=1}^{n} (X_k - X_{k-1})(Y_k - Y_{k-1}) \quad (7)$$

where G_α is the Gini index value for a population or sample α, X_k is the cumulative proportion of the population endowed with attribute k (in this case transit connectivity) for k=0,…,n, and Y_k is the cumulative proportion of attribute k.

4. Case study

The proposed framework is applied to a comprehensive data set of housing parcels, subsidized housing locations and the entire transit network in the city of Baltimore. As of the 2010 census, the city has a total population of 620,961, which is predominately African America (63.6%) with an average per capita income of \$23,853 and median household income of \$40,100; 22.4% of the population lives below the poverty level. This is compared to the state of Maryland with a 30% African American population, per capita income of \$35,751 and median household income of \$72,419. The economic prospects of Baltimore residents are significantly bleaker than the rest of the state in general. Baltimore makes a good case study, because like many other large cities, there are high levels of concentrated poverty, a large base of

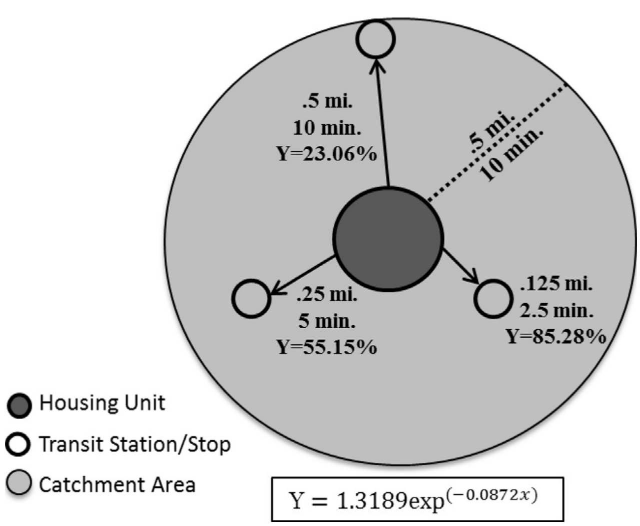

Fig. 1. Transit catchment area and distance decay function calculation for housing units.

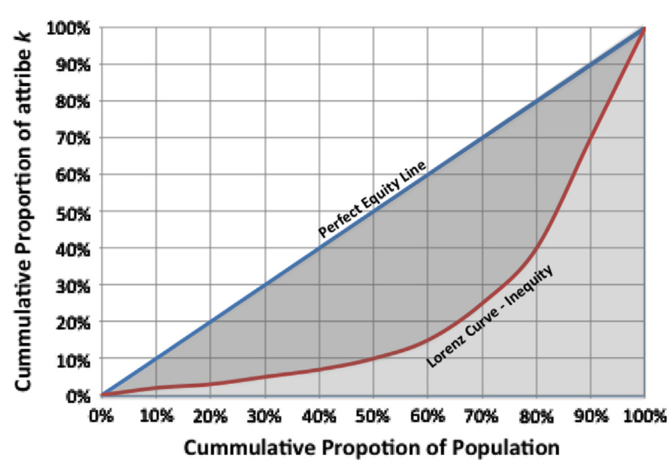

Fig. 2. Example of a graphed Gini index with perfect equity and Lorenz curves.

residents that either use or qualify for subsidized housing, many concerns with issues of spatial mismatch and an extensive public transit network. The concerns Baltimore faces, are similar to those of other large cities with well-developed public transport systems and a growing subsidized housing base.

4.1. Transit system

The complete Baltimore City transit network is adapted from Maryland State Highway Administration data. The transit database consists of Maryland Transit Administration's (MTA) bus and rail networks. MTA is a state-operated mass transit administration in Maryland. MTA operates a comprehensive transit system throughout the Baltimore-Washington Metropolitan Area. There are 77 bus lines serving Baltimore's public transportation needs. The system has a daily ridership of nearly 300,000 passengers along with other services that include light rail, Metro subway, and the MARC (commuter) Train. The Baltimore Metro subway is the 11th most heavily used system in the U.S. with nearly 56,000 daily riders. Nearly half the population of Baltimore lack access to a car (Brookings Institute, 2011), thus the MTA is an important part of the regional transit picture. The system has many connections to other transit agencies including the extensive Washington Metropolitan Area Transit Authority (WMATA) network, the Downtown Baltimore Charm City Circulator and adjacent county transit systems, including Howard Transit, Connect-A-Ride, Annapolis Transit, Rabbit Transit, Ride-On, and TransIT. Fig. 3 shows MTA bus and rail for the entire city of Baltimore. The Baltimore transit system is connected to the larger WMATA transit network via the MARC commuter rail line. This system has a daily ridership of over 31,000 (Dickens et al., 2011).

Transit access for households within the city of Baltimore is fairly ubiquitous. Nearly 68% of households in the city are with a 5-min (straight-line) walk to a public transit stop and 94% are within a 10-min walk. For LIHTC units, there is a much greater proximity to transit stops, 84% of units are within a 5-min walk and 98% are within a 10-min walk. Section 8 units are even closer to transit stops with 98% and 100% within five and 10 min walks, respectively. The ubiquity of transit access in Baltimore, necessitates a more complex measure of transit proximity; one that incorporates the quality of service at a particular stop, its connectivity to the rest of the transit system and the ease of access to destinations across the city, in order to better gauge the utility of transit proximity.

4.2. Subsidized housing

Fig. 4 shows the location of subsidized housing units used in the analysis. The data comes from HUD's database on LIHTC project locations and Section 8 locations from the National Housing Trust. Each project is scaled on the map based on the number of subsidized units at each project. The HUD locations are shown in proximity to bus and rail stops. The gray background is the centroids of all market-rate residential housing units used in the analysis.

5. Results

This section presents the results of the methods described in the previous sections for the multimodal network in the city of Baltimore. The analysis of transit equity in the region focuses on the distribution of transit connectivity for housing units subsidized by HUD under the Section 8 and LIHTC programs.

Fig. 5 shows the connectivity results for transit in the City of Baltimore at the transit stop level. As the map shows, most of the transit connectivity in concentrated at the city center with some well-connected nodes in the center along routes going north and south. The higher connectivity is generally for rail transit nodes,

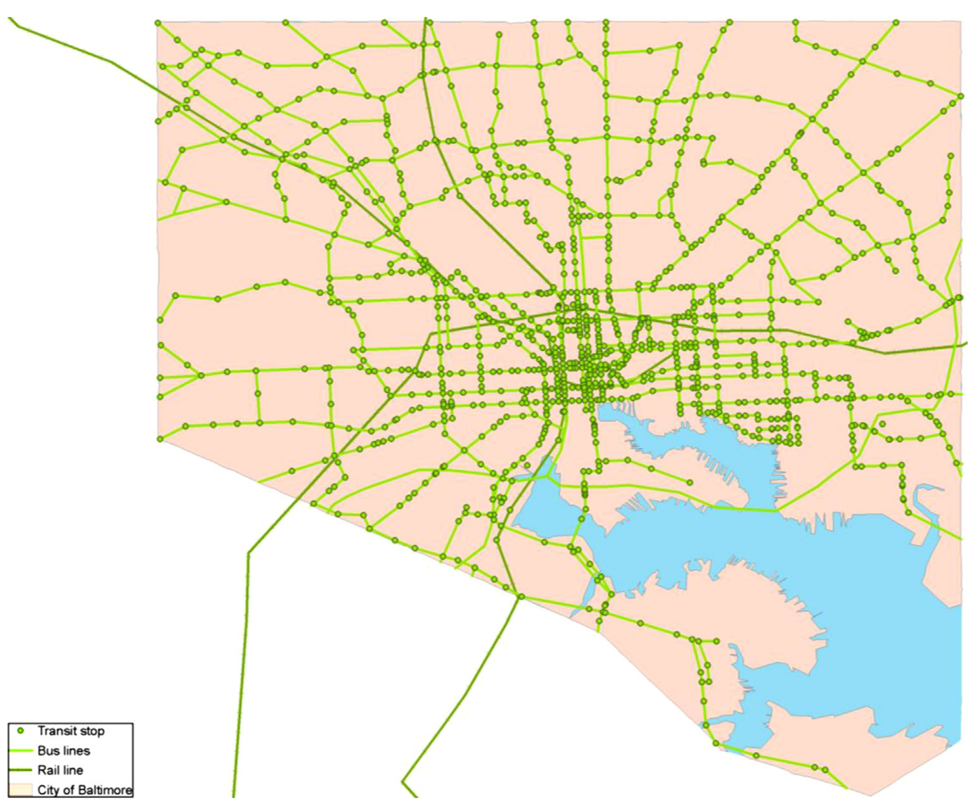

Fig. 3. Baltimore city transit route and stop configuration.

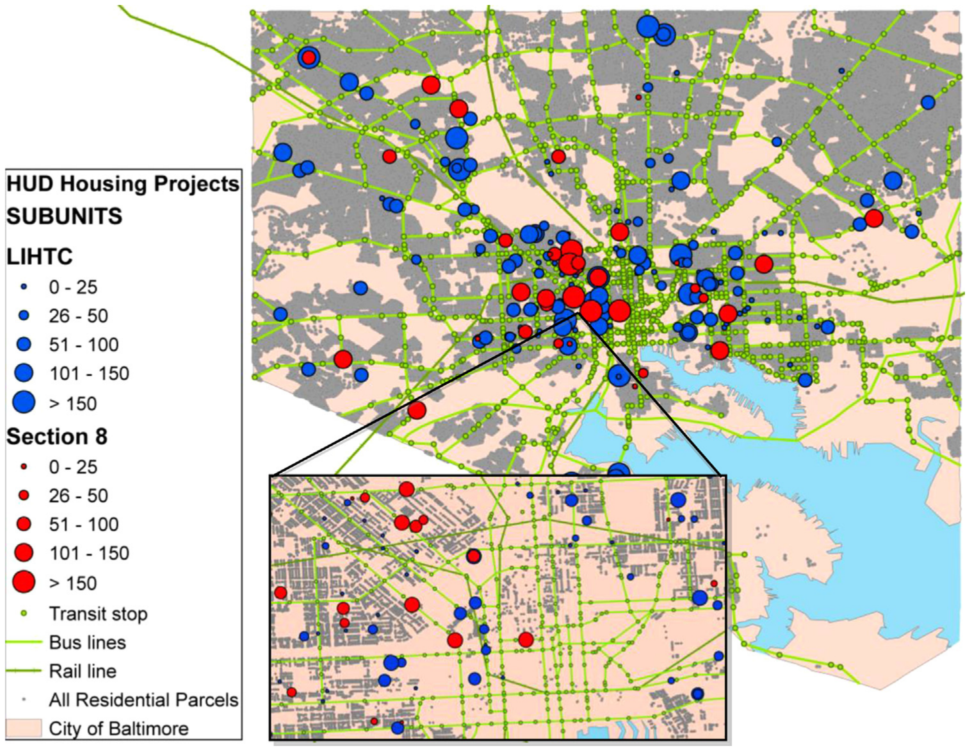

Fig. 4. Transit routes, stops and individual housing unit locations in Baltimore city.

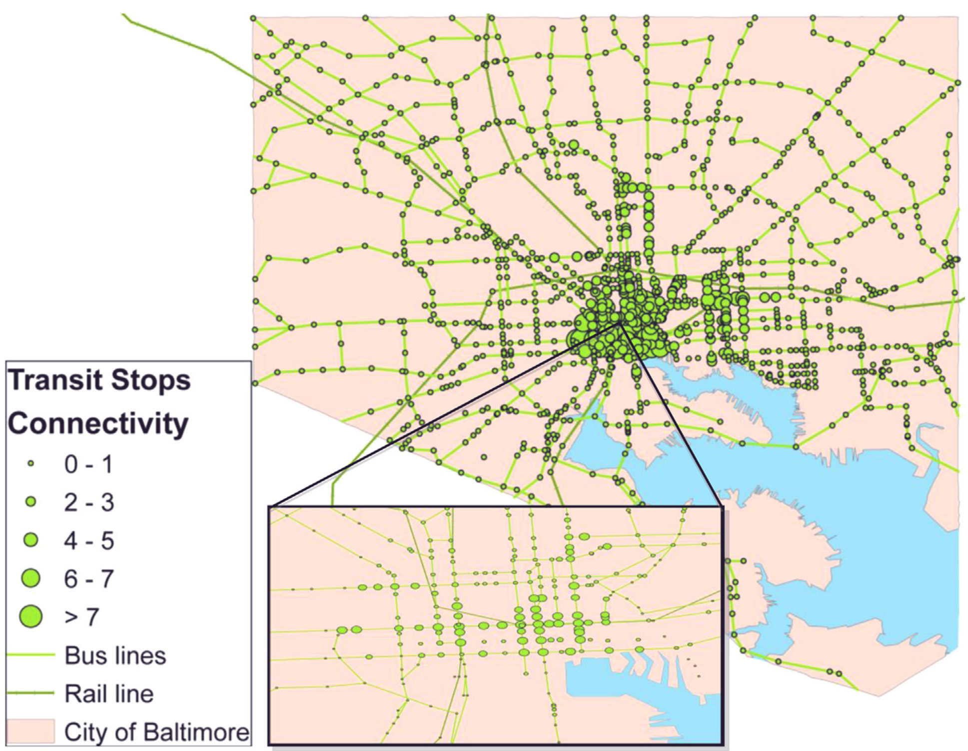

Fig. 5. Transit service connectivity index results for Baltimore city.

though some bus lines with higher frequencies and connections to rail achieve high connectivity scores.

Table 1 provides a summary of the inequality index results for the entire population of housing units in Baltimore, all LIHTC, Sections 8 and combined units and for 50 random samples of the housing unit population. In the context of this paper, the population figure is used to describe the distribution of transit among the population of housing units and serves as a point of comparison for programs that encourage more equitable transit distributions.

HUD encourages project locations in proximity to transit. The combined connectivity and Gini index serves as one tool to determine if the transit proximity (1) provides good access and mobility potential and (2) if that access is equal for all subsidized units or if high quality access is available for a few units and moderate connectivity is accessible to the rest and (3) if the program in question actually achieves the goal of better transit access for all units compared to the population or a random sample (that is, can the same equity score of the policy oriented approach be achieved simply by selecting random at units).

In our dataset, there are 15,143 subsidized housing units. To determine if transportation and housing policy goals are working, a boot strap method is used to obtain the mean, variance, standard deviation and confidence interval of the Gini Index for a random sample of housing units in the study area (Table 1). Using the set of random samples, it can then be determined if the distribution of transit connectivity is more equitable for subsidized units compared to the likely outcome if the location of those units were simply placed at random.

Table 2 first provides summary statistics for the population, the samples and the subsidized units. The first gauge of access to transit is the average connectivity for all units. This measure is the one that most closely approximates the traditional transit access assessments. HUD subsidized units do appear to have much higher connectivity scores on average than both the population and the three random samples. However, this is only an indication that *some* units are well connected. This does not indicate whether all units have access to quality transit or just a few with very high connectivity, which skew the mean.

One common measure of success in locating units in proximity to transit is the distance to a transit stop. Table 2 measures the average distance from specific housing unit samples to the nearest transit stop (either rail or bus). The location of subsidized housing units is on average much closer to transit than the general population. When the analysis is restricted to units within a half-mile of transit the results show that subsidized housing units are again generally closer in space to transit stops than when compared to the general population. The figure does not change at either level of analysis for Section 8 housing, which indicates all housing is within half a mile. This measure, though commonly used in policy analysis, does not provide a complete picture of the real access to transit or quality of connectivity across all housing units. To do this, there must be a measure of the quality of service at each transit stop.

The last measure reported in Table 2 essentially combines these other analyses into a single, comparable index number. The results show that when all subsidized units are combined into a single index, transit connectivity appears to be more equitably distributed than in the general population or for a random sample. When the two types of subsidized unit are separated out, the results show that transit is much more equitably distributed among Section 8 housing units than among LIHTC units. The LIHTC units have a higher index score than the general population or the random samples, which indicates that transit connectivity is concentrated for a few units and the rest have access to much less or lower quality transit.

Table 1
Random sample statistics.

Descriptive statistics	
N	50 (samples of 15,143)
Mean	0.70657
Min	0.70033
Max	0.71539
Variance	0.00001
Standard deviation	0.00363

Table 2
Transit and housing inequality index results.

Data set	Housing units	Average connectivity score	Distance to transit (feet)		Gini coefficient
			All stops	Stops w/in.5 mile	
Population	243,883	11.63	807	774	0.7083
LIHTC units	11,038	33.67	572	559	0.7150
Section 8 units	4,129	63.23	381	381	0.6234
All HUD units	15,147	41.69	535	523	0.6905
Random samples	15,147	11.59			0.7066

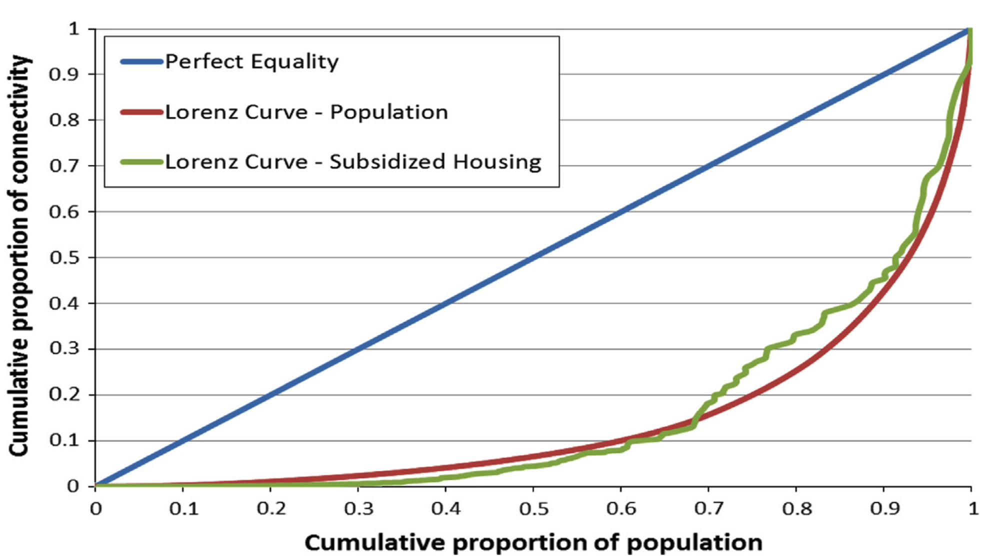

Fig. 6. Transit service Gini index results with Lorenz curves by housing unit type in Baltimore city.

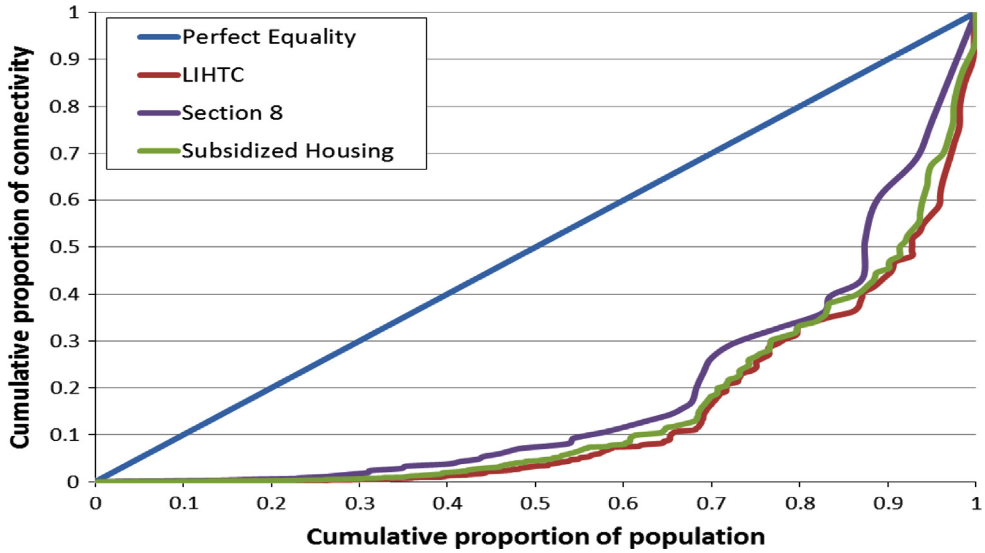

Fig. 7. Transit service Gini index results with Lorenz curves for subsidized housing units in Baltimore city.

Table 3
Transit equity hypothesis test results.

	LIHTC	Section 8 (s8)	All subsidized units (ASU)
H_0	$G_{(\mathrm{LIHTC})}=G_{(\mu)}$	$G_{(s8)}=G_{(\mu)}$	$G_{(\mathrm{ASU})}=G_{(\mu)}$
H_a	$G_{(\mathrm{LIHTC})}<>G_{(\mu)}$	$G_{(s8)}<>G_{(\mu)}$	$G_{(\mathrm{ASU})}<>G_{(\mu)}$
T-test	−16.41774	161.96409	31.29356
P-value (.01, 99% CI)	2.68	2.68	2.68
Result	Reject null	Reject null	Reject null

Fig. 6 provides the graphical representations of the Lorenz curves calculated from Table 2. As the figure shows, aggregate subsidized housing units have a slightly more equitable distribution of connectivity compared to the general population of housing units. This is evidenced by the Lorenz curve for subsidized units where the curve more coterminous with the equity line.

When the two types of subsidized housing units are separated out in Fig. 7, the improvement in equity for Section 8 housing becomes apparent. Section 8 housing stands out in comparison to LIHTC units, for access and connectivity.

To determine if subsidized housing is meeting the federal and policy-specific goal of transit equity, a simple hypothesis test is used. The null hypothesis is the Gini coefficient for subsidized housing units is equal to the mean sample Gini Coefficient (μ). In the alternative, if the distribution is less equitable, the index value for subsidized units will be greater than the sample mean. If the distribution is more equitable, the index will be less than the mean of the sample. The hypothesis test results are provided in Table 3. The required P-value for a 99% confidence interval is about 2.68. The two-sided T-test shows a very high value, for all housing unit types, indicating that the test results are well within the 99% confidence level.

LIHTC transit units have a Gini coefficient higher than the sample mean (see Table 2), indicating that the distribution of transit connectivity and access is less equitable than if the housing units were randomly placed in the city. The hypothesis test confirms this result with 99% confidence, rejecting the null hypothesis and accepting the alternative. On the other hand, Section 8 units have a Gini coefficient much lower than the sample mean, with an extremely high T-statistic, leading to the rejection of the null hypothesis and statistical confirmation that transit access is more equitably distributed among Section 8 units than could be achieved by randomly placing the units.

6. Summary and conclusions

Access to transit for all members of vulnerable classes, is a critical goal for all U.S. federal agencies and many international organizations. The HUD and DOT have both made specific proclamations and created program goals aimed at increasing the equitable distribution of resources to these groups. The agencies have program goals to increase the supply of affordable housing and better distribute transportation access among that supply. Specific policy goals within the HUD's LIHTC program, work to provide an advantage to developers interested in supplying low-income rental units near transit.

Despite clear policy emphasis, the results of these programs appear to have little influence in enhancing the distribution transit access and service amount subsidized housing units. This paper first developed a transit connectivity index to measure the quality of public transportation service at every rail and bus stop in the city of Baltimore Maryland. Then, using parcel level data, the location of all market rate and subsidized housing units was determined and a measure of accessibility to transit service was calculated. A joint connectivity and equity index was constructed to determine if HUD subsidized housing programs actually resulted in better transit equity outcomes for low-income residents.

The results indicate that while HUD units generally enjoy closer proximity to higher quality transit, the distribution of this access is not equitable among these units. Where traditional measures of transit access and service might declare higher levels of transit proximity a programmatic success, the analysis goes a step further to measure the spatial distribution of transit service quality. For LIHTC units the distribution of transit is less equitable than it is for a mean distribution among 50 random samples of all Baltimore housing units and the general population of market rate housing. This indicates that the LIHTC points system for Baltimore housing units is no more effective at providing all units with high quality public transportation access than if the locations were randomly selected. Section 8 housing has a more equitable distribution of transit among its units. Compared to the market-rate population and 50 random samples, the program has a more equitable distribution of transit service.

Section 8 units tend to be more spatially aggregated and located in more transit abundant areas of the city. While one could argue the negative effects of geographically concentrating low-income units, one positive result of this concentration is that Section 8 participants as a whole appear to have better access to opportunity through public transportation. The LIHTC program units are much less concentrated and are often located near poorly connected transit stops. While LIHTC residents are better integrated with the surrounding community, Section 8 participants and the general population of the city have much better access to quality transit and by extension, economic opportunity.

6.1. Policy implications

There are several ways in which housing and public transport policy can be enhanced to better meet the goals of equity and environmental justice. This paper begins what ought to be an ongoing discussion on what public transit means for low-income households. Statistically driven analysis like what is presented in this paper can often seem too abstract to decision-makers looking to make real changes to transit networks and housing policy. Certainly, in absolute numbers the equity results in this paper seem small, but even tiny changes in the overall distribution of transit service among subsidized housing units can make a big difference in one's ability to participate in a range of social and economic activity. Faster, more reliable transit service that connects those that rely on this mode with opportunities for employment may significantly improve the economic condition of many residents.

For US housing policy specifically, an increase points and preference for LIHTC projects (not just in Maryland, but for all states) that will be sited close to high connectivity and accessibility transit stops, will lead to more access for a larger portion of the low-income population. For policies that seek transit proximity in general, more emphasis should be placed on transit locations with high connectivity rather than simply distance to any transit stop. Policies should also ensure that transit stops provide sufficient access to meaningful destinations. Such locations have higher levels of activity density and an activity composition with suitable employment and affordable shopping opportunities for low-income populations. When the location of vulnerable populations, housing units or transit service is fixed, increasing speed, frequency and capacity of transit lines that serve subsidized housing units may temporarily aide in providing better transit equity. For future developments, enhancing transit characteristics at a few suitable development locations and encouraging the construction of affordable units can significantly increase equity.

With a few policy improvements the availability of high quality transit for all residents of affordable housing units can be assured. Traditional measures of transit access, which rely only on service frequency or proximity, may not adequately measure transit equity. New tools like the connectivity and Gini index developed in this paper can enhance policy assessment to determine if federal policies are meeting their mandates. Future research could focus on the equity implications of transit characteristic changes including enhancements to frequency, speed, transfers or fares.

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