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A measure of equity for public transit connectivity

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ABSTRACT

An equitable transit system can cater to the needs of captive riders and maximize transit service coverage. Historically transit equity has not considered in planning or has been an afterthought in the process; leading to the underutilization of transit and encouraging travelers to be auto dependent. In this paper, the authors propose a methodology to estimate transit equity using a number of attributes such as frequency, speed, capacity, and built environment in a multi-modal transit network. We propose a methodology to measure transit equity from a graph theoretical approach for all levels of transit service coverage integrating routes, schedules, socio-economic, demographic and spatial activity patterns.

The objective of using equity is to quantify and evaluate transit service in terms of prioritizing transit locations for funding; conforming with federal regulations; providing service delivery strategies, especially for areas with large multi-jurisdictional, multi-modal transit networks; providing an indicator of multi-level transit capacity for planning purposes and assessing the effectiveness and efficiency for node/stop prioritization while choosing transit as a mode of travel. The methodology uses a stylized connectivity measure with a Gini index for equity estimation at different levels such as stop, line, zone and area. An example problem is presented to demonstrate the proposed methodology. The approach is then applied to the Washington–Baltimore region in the United States. The results show the existing transit service coverage at different locations. The proposed approach can be utilized as a tool for transit service planning.

1. Introduction

Transportation service planning is a complex and multifaceted task. In addition to planning for access based on transit coverage, considerations such as service frequency, stop location, and daily operations, among others, must be included in analyses of transit equity. However, due to the complexity of transit networks and the scale of urban areas the networks typically serve, limited research has been conducted on developing a tool to measure equity as it relates to the distribution of quality transit access in a region.

The importance of transit service equity first emerged with the Civil Rights Act of 1964. Title VI of the Act established the directive that all federal agencies must distribute federal resources equitably in such a way as to maintain quality of services so that resources are provided in the fairest and least discriminatory manner possible (Colopy, 1994). As federal agencies, both the United States Department of Transportation (USDOT) and the Federal Transit Authority (FTA) are required to conform to equity standards. The directive for equity in transit was further solidified by Executive Order 12898, signed by President Clinton in 1994, mandating that all federal agencies address issues of equity. This mandate was implemented broadly for transportation issues with the Transportation Equity Act for the 21st Century (TEA-21).

This combination of legislation has led to the requirement that all federal, state, and local transit agencies receiving federal funds establish policies and standards that distribute transit service equitably based on a minimum five-criteria basis, including vehicle loads, vehicle assignment, vehicle headway, distribution of transit amenities, and transit access (Pucher, 1982). Any organization that receives federal funding (in this case, from the FTA) is required to distribute services equitably. This requirement exists to mitigate instances of either disparate impact (unintentional) or disparate treatment (intentional). Transit agencies and service providers in urbanized areas with a population of 200,000 or more, where a major service change or fare change has been proposed, must conduct equity analysis (Thompson, 1998). Equity analysis is further complicated by the multifaceted definition of the term equity. Generally, the term represents two types of equity: vertical and horizontal. Vertical equity is perhaps the broadest definition, where (in the context of transit) those that pay the most should

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receive the most benefit. Horizontal equity is concerned with the equal treatment of those with equal means. In a transportation planning context, horizontal equity can be used to measure how all households (setting the household as an equal unit) benefit from transit service. While there may be planning situations where it is desirable to provide more benefits to those that pay more, or to ensure certain economic groups have equal access to transit service, we take a broad approach to horizontal equity to measure how equitable the distribution of public transportation service is to all households across two major transit agency service areas in the Washington–Baltimore region. Thus, the unit of analysis is each household as a potential transit rider rather than the income of a household.

The method of analysis used to determine equity is generally left to the agencies to establish appropriate measures. Because of the great variation in analysis, the possibility of subjectivity, and the lack of established required variables, it is possible that changes in services could cause undetected disparate impacts. While the literature develops a much more focused approach to measure equity as it relates to transit service distribution (see Delbosc and Currie, 2011), the typical measure of service is overly simplistic to quantify the quality of service distribution adequately. Further, many of the service measures developed in the literature do not incorporate the minimum criteria for Federal equity analysis (vehicle loads, vehicle assignment, vehicle headway, distribution of transit amenities, and transit access). Many of the existing measures focus solely on vehicle headways or access. To aid in establishing a scientifically robust and analytically objective framework that incorporates these criteria, we propose a method to quantify the quality of service at each transit node in a network. This is combined with a tool to measure the inequity (concentration of quality service) at several geographic scales, combining the required equity related transit-service measures into a single service, access, and equity index. This measure improves upon the methods employed by previous studies by using a service measure that incorporates the quantification of access, service, and mobility. The primary purpose of this framework is to establish a tool that planners can use to understand more clearly the distribution of public transit service. The distribution of this index is measured within the Washington–Baltimore region in the United States. A primary focus is on transit equity within two locations with widely disparate transportation systems: the city of Baltimore and Prince George's County.

The remainder of this paper is organized into six sections. Section 1 presents a review of the related literature, followed by a presentation of the methodological framework developed to analyze the issue of transit connectivity, access, and equity in Section 2. Section 3 provides a sample problem to illustrate the methodology. Section 4 describes the case-study area. Results of the method application are presented in Section 5, followed by conclusions, policy implications, and suggestions for further research in Section 6.

2. Related literature

This paper focuses on two important components of transportation system evaluation: measurements of the distribution of transit service and measurements of supply. We divide the literature into two parts, following these major components.

2.1. Measures of equity

Equity is a multi-disciplinary term that has been used in a variety of ways. A multitude of issues have been examined under the context of equity in the literature. In geography, equity has been used as a framework to examine the distribution of opportunities to access economic activity (Keeble et al., 1982) or the distribution of particular services (Truelove, 1993) among the population. In medicine, equity has been used to measure the segmentation of population and its implications for health-care services (Bloom, 2001). In the same field, disparate impacts of the location of health-care facilities among the population have been measured (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 in the context of income distribution, and in political science it has been used commonly for welfare analysis (Maniquet and Sprumont, 2005).

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 equal distribution of an attribute (or recourse) among equal members of a population. For example, do all welfare recipients have the same access to transportation? Vertical equity focuses on the distribution of an attribute among specific groups (Mooney, 1996). An example is the progressive tax system, where higher income earners pay a greater amount of tax. The focus of this paper is horizontal equity. To this end, we treat all households as equal, with each one containing a number of potential transit riders. The test for equity, then, is how well quality transit (defined as an index of access and connectivity) is distributed among households in the study area.

Despite several federal mandates, there is no generally accepted standard framework for measuring equity in transport. Litman (2002) surveyed the available data and existing studies for transportation equity, finding a large variation in the measurement of transportation (mobility verses accessibility), the type of equity considered (horizontal versus vertical), and the measures of effectiveness used to calculate distribution (passenger miles, frequency, cost, etc.). Early discussions of transport equity in the literature revolved around a more economic basis, considering how public transit changed consumer welfare and profit maximization (Hay, 1993; O'Sullivan and Ralston, 1980). Hodge (1995) provides a larger context for economically based transportation equity, arguing that transportation investments often affect different classes and races disproportionality, where the burden to pay for transportation investments is not always equal to the benefit enjoyed. This is something that should be considered in the planning process. Later, the focus turned towards a more socially oriented consideration of equity, with attention to how public transportation access was distributed amongst captive or low-income riders (Garrett and Taylor, 1999). This form of equity analysis has become the de facto measure of distribution. Parallel to this, much work was done to analyze how public transport might aide in bridging the gap between welfare recipients and job location (Blumenberg and Ong, 2001; Cervero et al., 2002; Sawicki and Moody, 2000). Included in this type of equity analysis is how public transport can contribute to or reduce the incidence of social exclusion (Kenyon et al., 2002; Lucas, 2006; Preston and Rajé, 2007).

Golub (2010) used a utility function to model welfare impacts for service change scenarios. Delmelle and Casas (2012) measured the distribution of transit access among different population groups in Cali, Colombia, finding that 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 resulted in the greatest transit equity for low-income groups in Paris.

Only in a few papers has equity, in the sense that it has been used in the rest of the literature, been applied to transit. Delbosc and Currie (2011) measured equity as it relates to the distribution of transit service frequency in Melbourne, Australia. Their results show an overall Gini coefficient of 0.68, indicating that roughly 70% of the population shares just 19% of the transit service.

2.2. Measures of supply

Measures of transportation supply are often synonymous with accessibility and mobility. That is, the supply of transport is often calculated by how well a potential rider can move about the city or by what places the rider can reach using the transport system. In terms of mobility related measures, perhaps the most common method, favored for its relative simplicity, is the frequency of service at a particular node or stop (Bowman and Turnquist, 1981; Sanchez et al., 2004). Another common measure of mobility related transportation supply at a more macro-level is the number of vehicle miles in a given area (Buehler, 2009). While these measures provide a simple numerical estimation about the quantity of transit opportunity at a particular node or in a region, they lack more important and more difficult variables that measure the quality of service.

Accessibility related measures tend to focus on how far households are from transit stops (Handy and Niemeier, 1997) or the length of journey from house to work with transit (Weber, 2003). Each of these measures is typically computed using GIS to determine the length of time a particular journey would take with each mode (O'Sullivan et al., 2000). Equity plays a role in these types of measures, as accessibility can differ significantly among groups (Kawabata, 2009). Murray and Davis (2001) established a measure of equity by measuring need (primarily an index dominated by income) and access (the availability of transit in a particular location), but do not incorporate the traditional measures of mobility and accessibility.

This paper takes a unique approach to measuring transit supply by blending seamlessly both mobility measures and accessibility measures with overall transit quality measures (connectivity) to assess the distribution of high-quality transit service in a region. This provides a framework for planners and policy-makers to measure equity objectively. First, we construct an index of transit connectivity that incorporates a graph theoretic approach to determine the performance of large-scale multi-modal transit networks. The purpose of the index is to quantify measures of connectivity within a transportation network at the node level. The connectivity index is constructed with an assessment of service quality that incorporates the unique characteristics of each transit line and stop, including frequency, speed, distance, capacity, required transfers, and activity density of the underlying land use served by a transit node. The result of the index is a measure of transit-service quality at each stop, along every transit line. This nodal connectivity index is then applied to a functional form of the Gini coefficient, a variant of the Lorenz curve, to measure the distribution of quality transit access in the region. The Gini coefficient measures the rank distribution along a linear Lorenz equity line, which represents the cumulative population share of a given attribute (Marshall and Olkin, 2007). This paper applies the methodology to several transit-service areas in the Washington-DC metro area to measure transit equity across the region.

3. Methodology

In this section we describe the methodology for measuring transit-service connectivity and equity. In the first part, we show the method for calculating transit connectivity. In the second part, we show how this is used to measure transit equity.

3.1. Connectivity

The common treatment of transit connectivity or service level in the literature is generally limited to 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. A list of notations used in this paper is provided in Appendix-A.

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. 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 operation 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 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, we have considered it to be the ratio of households and employment in a zone to the unit area. Mathematically, activity density is defined as:

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

The connectivity index measures the aggregate connecting power of all lines that are accessible to a given node. However, not all lines are equal. Nodes with access to many low-quality routes may attain a connectivity index score equal to a node with only a couple of very high-quality transit lines. This means that while both nodes are able to provide good access, the node with the fewest lines provides the most access with the lowest need to transfer. To scale the index scores based on the quality of individual lines, that is, scaling for the least number of transfers needed to reach the highest number and quality of destinations, the node scores are adjusted by the number of transit lines incident upon the node.

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:

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

where $T_{l,n}$ is the transfer scaled index of node n in a line l; $P^{t}_{l,n}$ is the total connecting power of line l at node n; Θ^{n}_{l} is the number of lines l at node n.

3.2. Transit catchment and accessibility

This paper seeks to measure the distribution of transit access among the population and for groups within the population. To determine accessibility to stops near a household for inclusion in 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. Thus, we formulate a distance-decay function to pro-rate the connectivity of transit nodes within a half-mile (Euclidian distance) of each unit based on its distance from the centroid of the residential parcel.

Eq. (5) represents the connectivity calculation for a station within the half-mile catchment area, where, ρz_1, n is the pro-rated connectivity and is defined as

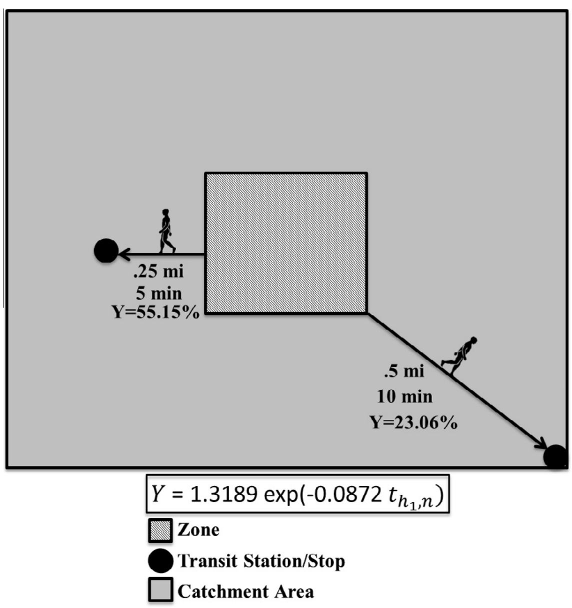

Fig. 1. Zonal transit catchment. *Source:* Created by Authors.

$$\rho_{z_1,n} = a \times \exp^{-bt_{h_1,n}} \tag{5}$$

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 node transit stop n. The parameters for a and b are from Kim et al. (2005) and are estimated based on empirical data.

Fig. 1 provides a simple example of the half-mile catchment area and the calculation of the pro-rated 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 transit nodes within the catchment area of each zone. Thus, a zone in a very dense transit area is made comparable to a zone in a less dense area. The following equation shows the connectivity index of a zone:

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

This service-quality index improves upon others, in that it uses not just service supply but the quality of access provided to all destinations. This measure represents a significant improvement over many service indexes, while maintaining tractability and practicality.

3.3. Inequality index

Inequity is a measure of the 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, which has traditionally been used to calculate the distribution of wealth among a population. The index measure is the difference between a perfect equity line (a straight line where, in the above example, 50% of income is held by 50% of the population), and a Lorenz curve, which measures the real distribution. 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. In this case, it becomes the cumulative proportion of

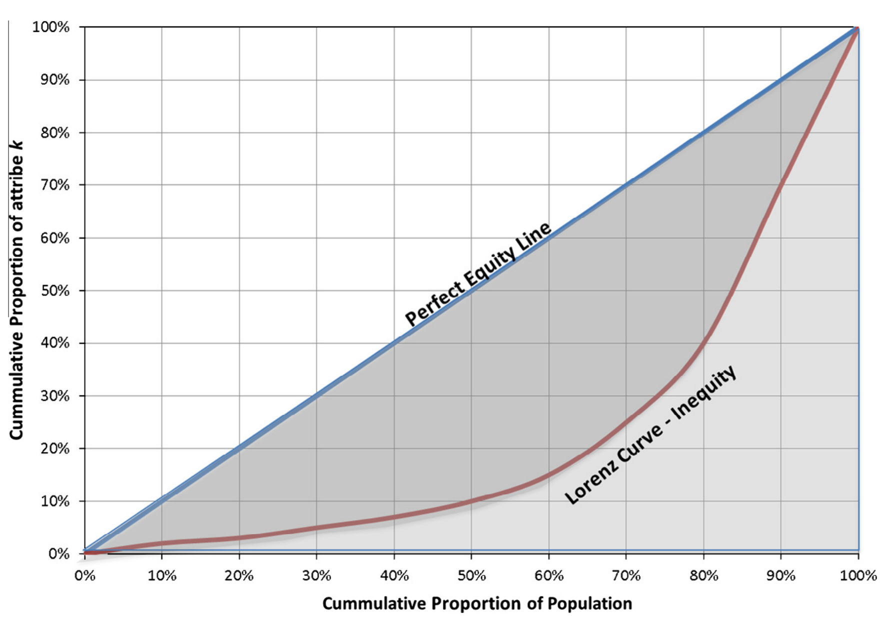

Fig. 2. GINI index example. *Source:* Created by Authors.

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 line below the equity line is the Lorenz curve, which represents the level of inequity. The Gini index essentially is the ratio of the dark shaded area (between the two lines) 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):

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

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 $k = 0,\ldots,n$, and Y_k is the cumulative proportion of attribute k.

4. Example problem

In this section, the methodology is described with the help of an example problem. The example network shown in Fig. 3a consists

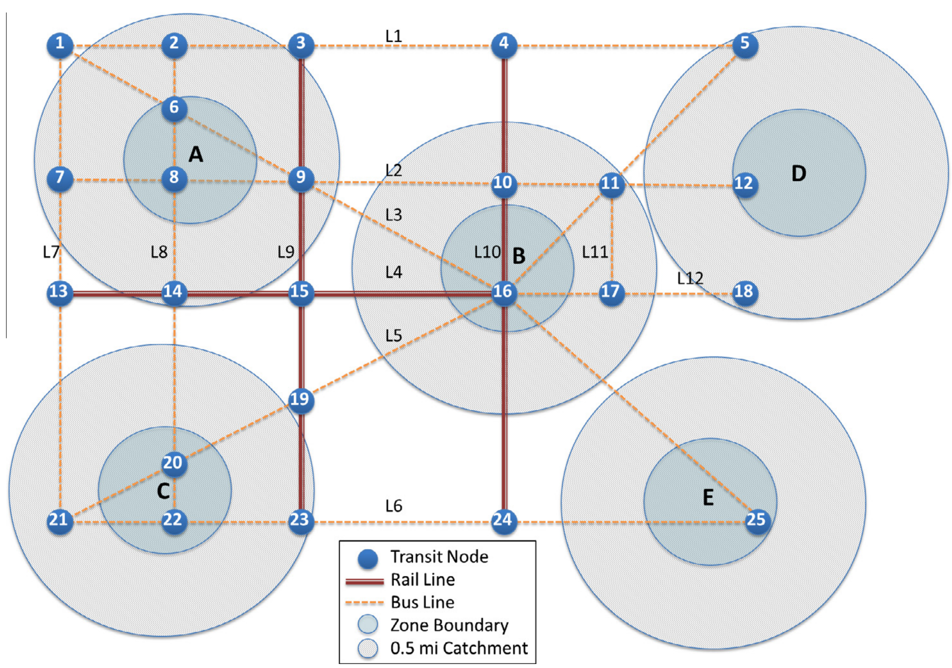

Fig. 3a. Example of transit system and zones. *Source:* Created by Authors.

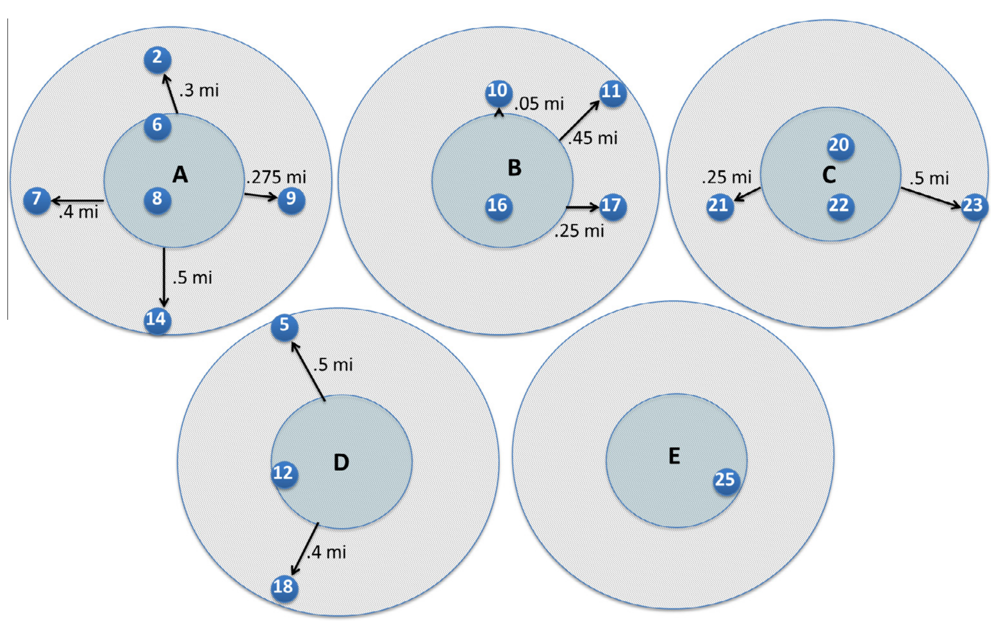

Fig. 3b. Walking distance to transit nodes in each zonal catchment. *Source:* Created by Authors.

Table 1
Example problem characteristics.

Line	Mode	Distance	Speed	Frequency	Operations	Capacity	Population	Employment	Density
1	Bus	20	10	30	24	50			
2	Bus	20	10	30	24	50			
3	Bus	26.15	18	15	48	75			
4	Rail	14	35	5	144	300			
5	Bus	26.15	18	15	48	75			
6	Bus	20	10	30	24	50			
7	Bus	16	10	30	24	50			
8	Bus	16	10	30	24	50			
9	Rail	16	30	10	72	300			
10	Rail	16	30	10	72	300			
11	Bus	4	10	30	24	50			
12	Bus	6	10	30	24	50			
Zone									
A							60	15	5
B							25	125	10
C							40	20	4
D							50	55	7
E							35	10	3

of (1) 25 stops, (2) 12 lines and (3) five zones with half-mile catchments. Fig. 3b shows each zone with the transit stops located in the zone and the distance in miles to stops that are within the half-mile catchment area.

Table 1 details the characteristics of each zone, transit line, and stop, such as population, density, operating speed, frequency, capacity, and number of operations. Each zone is attributed with a density measure, which is the ratio between the total population and employment for the zone and corresponding area.

Table 3
Sample problem connectivity results – zones.

Zone	$\rho_{n1,n}$	S_{ω}	$\sum P^t_{l,n}$	θ_{zu}
A	60	42	8.6230	12.3186
B	25	42	7.7041	4.5858
C	40	42	2.8654	2.7290
D	50	42	0.5276	0.6280
E	35	42	0.2000	0.1667

4.1. Connectivity

Table 2 shows the connectivity index results for the sample problem at the node level, while Table 3 shows the results at the zone level. The index results show that the centrally located zones, with higher-speed transit lines and easier access to opportunities (areas with high-activity density) have the highest connectivity, while outlying nodes have lower connectivity scores. Zone A has the highest zonal connectivity score due to its multi-modal transit network coverage, while zone E has the lowest score because it is connected by only one node and two bus lines.

Table 2
Sample problem connectivity results – nodes.

Node	$P^0_{l,n}$	$P^i_{l,n}$	$A_{l,n}$	$T_{l,n}$	$P^t_{l,n}$
1	0.8892	0.8892	0.6528	6	0.1482
2	0.1806	0.1806	0.6528	4	0.0452
3	9.9799	9.9799	1.4688	4	2.4950
4	6.6533	6.6533	0.9792	4	1.6633
5	1.2133	1.2133	0.9792	4	0.3033
6	0.9860	0.9860	0.8160	4	0.2465
7	0.1355	0.1355	0.4896	4	0.0339
8	0.2258	0.2258	0.8160	4	0.0564
9	11.5741	11.5741	1.4688	6	1.9290
10	7.7621	7.7621	1.1424	4	1.9405
11	1.4507	1.4507	1.1424	6	0.2418
12	0.1756	0.1756	1.1424	2	0.0878
13	17.8624	17.8624	1.3056	4	4.4656
14	17.8624	17.8624	1.3056	4	4.4656
15	29.6687	29.6687	1.4688	4	7.4172
16	36.5831	36.5831	1.6320	10	3.6583
17	0.0753	0.0753	0.9792	4	0.0188
18	0.0452	0.0452	0.9792	2	0.0226
19	8.8264	8.8264	1.1424	4	2.2066
20	0.7888	0.7888	0.6528	4	0.1972
21	0.4446	0.4446	0.3264	6	0.0741
22	0.1806	0.1806	0.6528	4	0.0452
23	7.7621	7.7621	1.1424	4	1.9405
24	3.3266	3.3266	0.4896	4	0.8317
25	0.6067	0.6067	0.4896	4	0.1517

4.2. Inequality index

The connectivity for each of the five zones is applied to the population distribution from the example problem. Table 4 shows the results of the index when applied to the example. The total GINI concentration ratio is .26789, which indicates that about 55% of the population shares 30% of the quality transit.

5. Case study

The proposed framework is applied to a comprehensive transit network in the Washington–Baltimore region. The complete transit network is adapted from Maryland State Highway Administration data. The transit database consists of two of the largest transit systems in the country: Washington Metropolitan Area Transit Authority (WMATA), and Maryland Transit Administration (MTA). The WMATA is a tri-jurisdictional government agency that operates transit service in the Washington, D.C., metropolitan area, including the Metrorail (rapid transit), Metrobus (fixed bus route), and MetroAccess (paratransit), and is jointly funded by the District of Columbia, together with jurisdictions in suburban Maryland and northern Virginia. Approximately $300 million are spent on the WMATA capital, operating, and maintenance costs, of which $150 million per year of available federal funds are required to be matched by $50 million in annual contributions from D.C., Northern Virginia, and suburban Maryland, each for 10 years. The use of federal funds by the agency means it is subject to federal equity standards. Additionally, the suburb of Prince George's

Table 4
Inequality Index of the Connectivity Distribution.

Zone	Connectivity	Proportion connectivity (Y)	Proportion population (X)	Cumulative proportion connectivity (Y_k)	Cumulative proportion population (X_k)	$Y_k - Y_{k-1}$	$X_k - X_{k-1}$	$(Y_k - Y_{k-1})$ $(X_k - X_{k-1})$
E	0.166691796	0.008159932	0.166666667	0.00816	0.16667	0.00816	0.16667	0.00136
D	0.628046954	0.030744288	0.238095238	0.03890	0.40476	0.04706	0.23810	0.01121
C	2.728992805	0.133590238	0.19047619	0.17249	0.59524	0.21140	0.19048	0.04027
B	4.585753362	0.224482777	0.119047619	0.39698	0.71429	0.56947	0.11905	0.06779
A	12.3186006	0.603022764	0.285714286	1.00000	1.00000	1.39698	0.28571	0.39914
	20	1	1					0.51976
						Gini's concentration ratio		0.48024

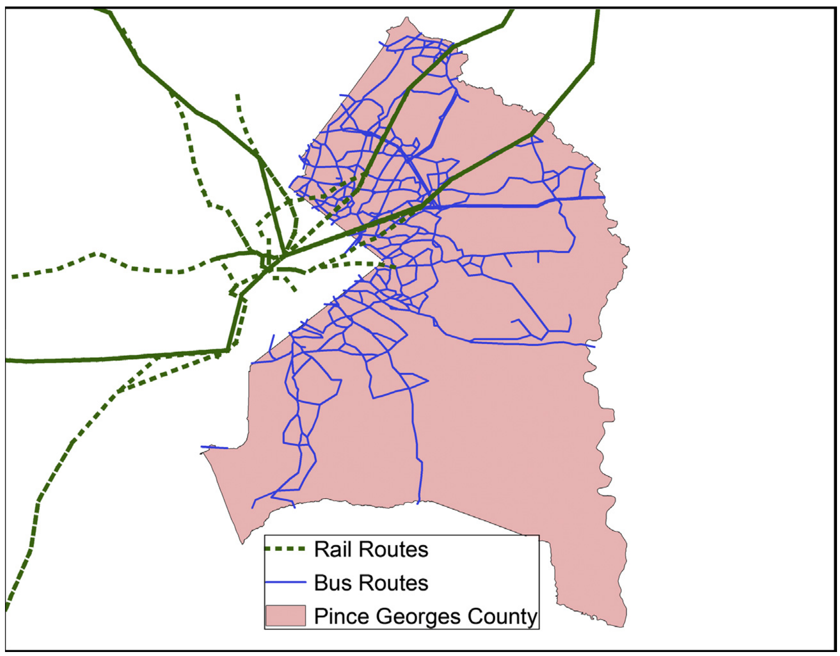

Fig. 4a. Transit routes in Prince George's County. *Source:* Created by Authors.

County is served by 'TheBus', a county-wide public transit system that provides 23 bus routes that generally service the WMATA metro stations.

The WMATA has the second highest rail ridership in the U.S. with over 950,000 passengers per day. This is second only to New York. The WMATA Metro provides an extensive heavy rail system with 106.3 route miles. The WMATA bus system also serves an extensive ridership of over 418,000 unlinked daily trips. TheBus has an average monthly ridership of over 340,000 unlinked passenger trips. Fig. 4a shows the transit network that serves Prince George's County.

MTA is a state-operated mass transit administration in Maryland, which operates a comprehensive transit system throughout the Washington–Baltimore 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 MARC train services. 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 lacks access to a car, thus the MTA is an important part of the regional transit picture. The system has many connections to other transit agencies in Central Maryland: the WMATA, Charm City Circulator, Howard Transit, Connect-A-Ride, Annapolis Transit, Rabbit Transit, Ride-On, and TransIT. Fig. 4b shows the MTA network around Baltimore. Both the WMATA Metro rail system and the Baltimore transit system are connected by the MARC commuter rail system. This system has a daily ridership of over 31,000. In the next section, results of the proposed methodology are discussed (Dickens et al., 2011). We focus on the results for the City of Baltimore and Prince George's County in a later section. The two locations offer significantly different transit-network patterns and provide an example of how changes in network topology affect the distribution of transit service. The complete methodology is integrated in a Geographic Information System (GIS) user interface using ArcInfo (ESRI, 2012).

6. Results

This section presents the results of the methods described in the previous sections as they are applied to the large-scale multimodal network spanning the Washington, D.C., and Baltimore region. The analysis of transit equity in the region focuses on five Maryland locations and the District of Columbia. Fig. 5 shows the location of each area included in the analysis and the transit lines that serve each location.

First, transit connectivity was calculated for each zone within an analysis location using Eqs. (1)–(6). Fig. 6a shows the connectivity

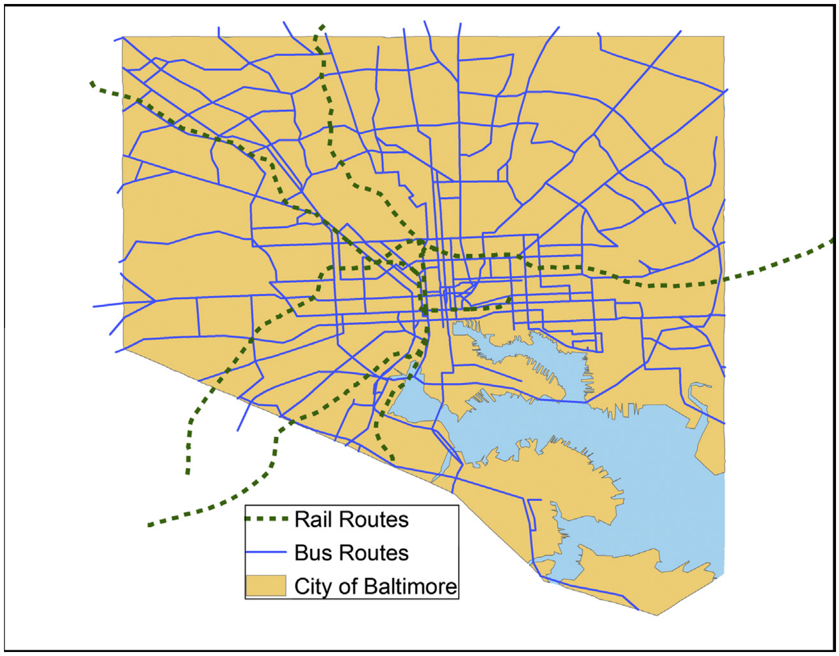

Fig. 4b. Transit routes in Baltimore. *Source:* Created by Authors.

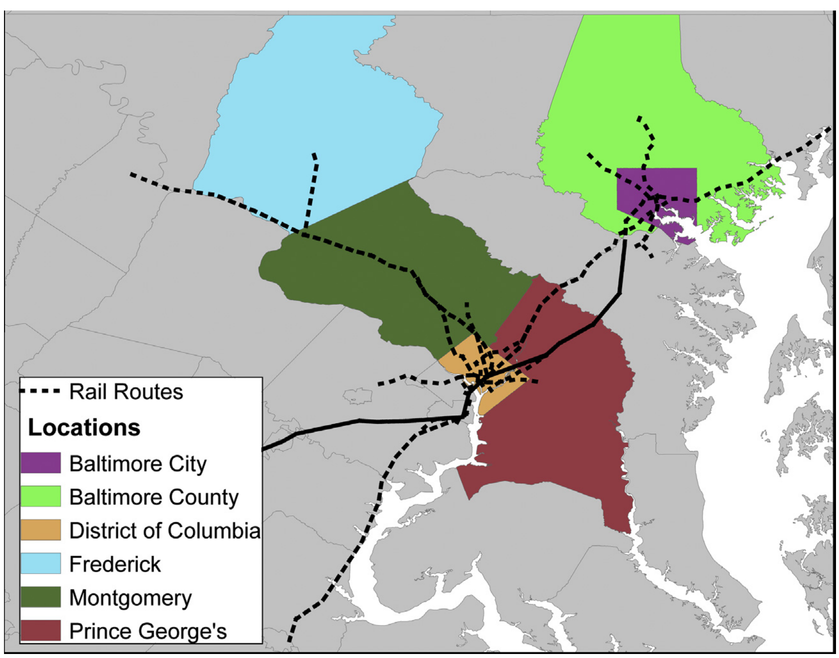

Fig. 5. Locations of equity analysis. *Source:* Created by Authors.

of each zone for every analysis location. In the figure, areas that are a shade of green have high levels of connectivity under the definition offered in the earlier sections of this paper. Areas that are orange have very low connectivity, and red[1] areas have no transit connectivity. The map clearly shows that areas with major transit service are higher in connectivity. Service in the Washington–Baltimore region tends to be concentrated in the urban core and radiates out with lower degrees of connectivity.

Figs. 6b and 6c show the connectivity for each zone within the Prince George's and Baltimore analysis areas. In Prince George's County, connectivity is best around the DC border (left side cut out), with some level of service with much lower connectivity throughout the county. In Baltimore, connectivity generally is concentrated around the central part of the city, though the northeast has some higher levels of connectivity as well. This area is the primary location of most metro and other rail service, with several good bus line connections.

Fig. 7a shows the percent of total analysis location households that are in each zone. For this paper, households are the proxy for population. In the analysis, connectivity equity is analyzed in the context of its distribution among households.

[1] For interpretation of color in Fig. 6a, the reader is referred to the web version of this article.

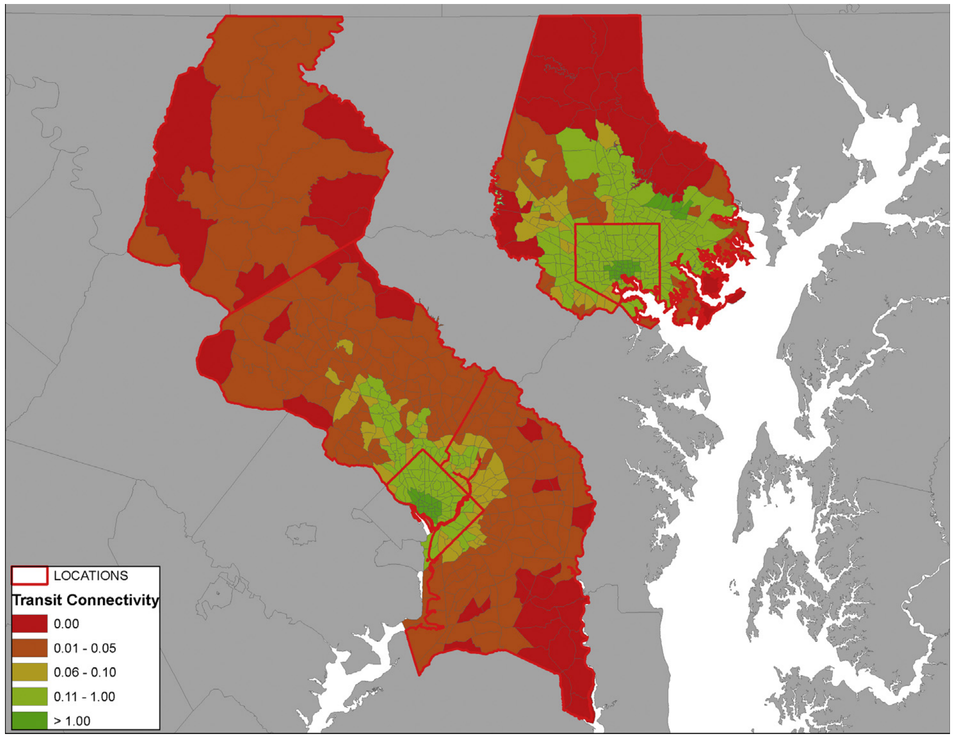

Fig. 6a. Connectivity index at the zone level. *Source:* Created by Authors.

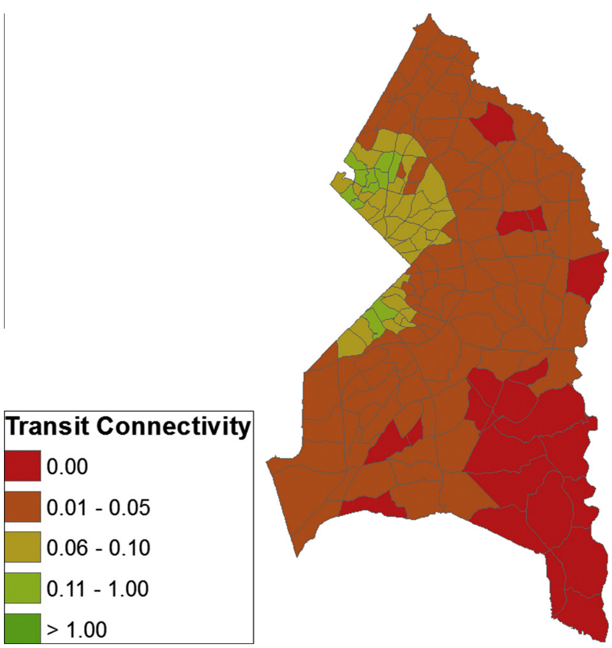

Fig. 6b. Connectivity index for Prince George's. *Source:* Created by Authors.

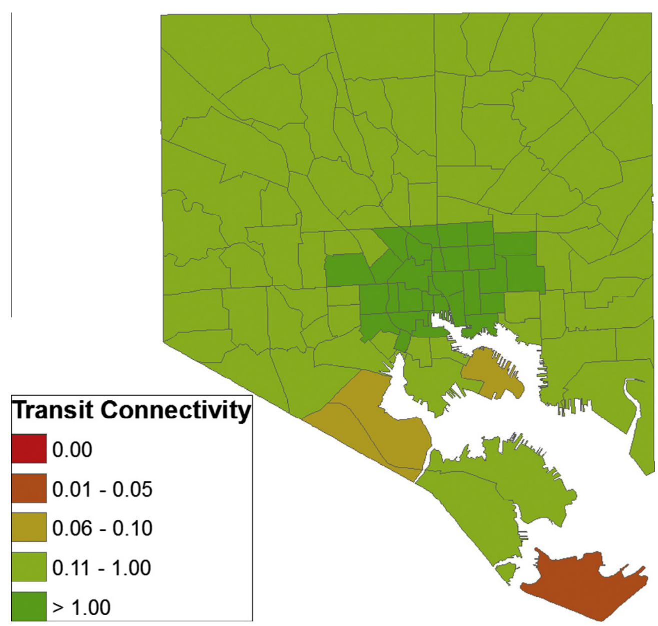

Fig. 6c. Connectivity index for Baltimore. *Source:* Created by Authors.

Figs. 7b and 7c show Prince George's County and Baltimore household distributions, respectively. In Prince George's, households tend to be concentrated more near the D.C. border. In Baltimore, the distribution of households tends to be away from the central city. There is a significant percent of households in the northwest areas of the city and to the southwest of the harbor.

Comparing the household distribution maps in conjunction with the connectivity maps provides an indication of the likely transit equity outcome. In Prince George's, the connectivity of the transit service is spread around the D.C. border, interspersed among the population. In Baltimore, much of the high-quality transit connectivity is in the central parts of the city, while the majority of households are located outside of the city center.

Table 5 provides a summary of the inequality index results for five locations in Maryland and Washington, D.C. These scores differ based on the topology of transit systems. There are many reasons that transit agencies may desire either concentrated transit connectivity or a more diffuse level of service. These scores set out a tool to evaluate specific program goals; as such, this paper does not attempt to determine whether higher Gini Index scores are

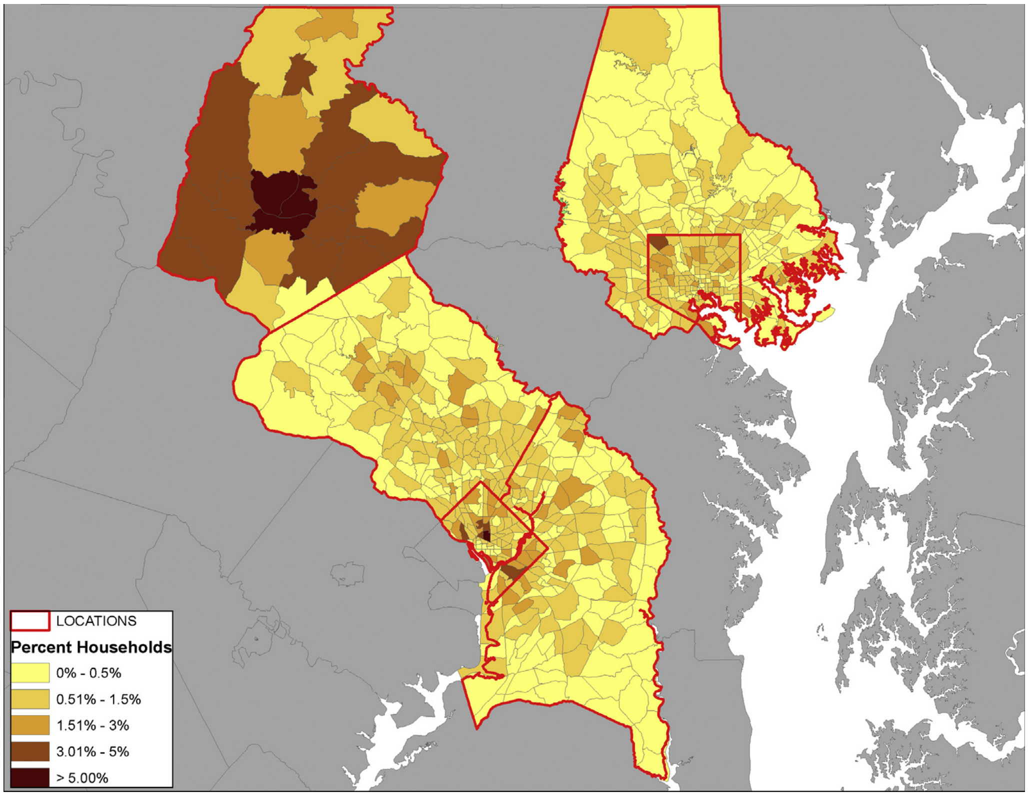

Fig. 7a. Percent households in zones for locations. *Source:* Created by Authors.

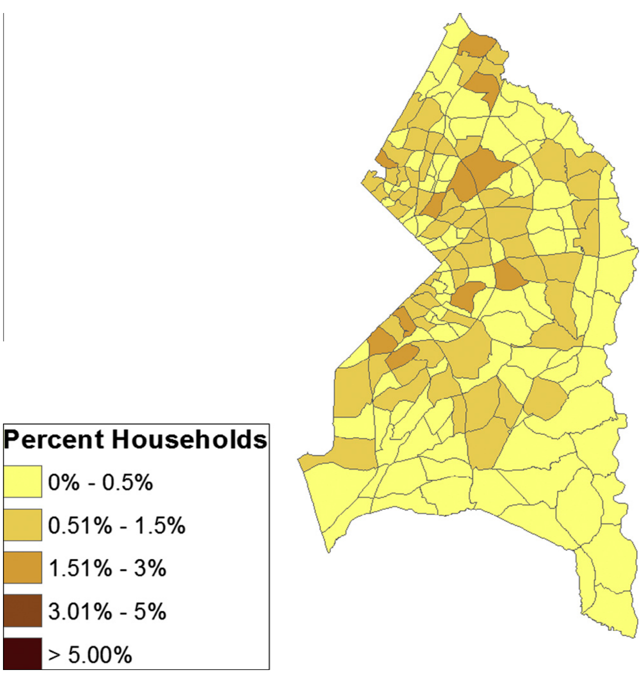

Fig. 7b. Percent households Prince George's. *Source:* Created by Authors.

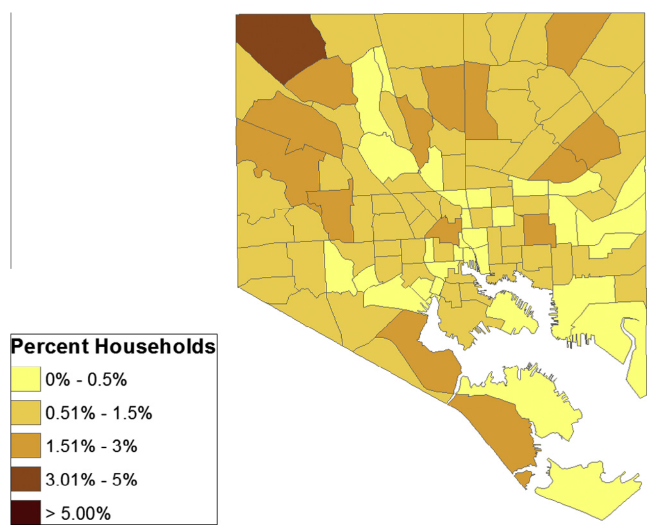

Fig. 7c. Percent households Baltimore. *Source:* Created by Authors.

good or bad. The scores, however, do provide an indication of how well distributed quality service is within a study area. If an agency goal is to spread high-quality transit service among all households, the scores should be evaluated with a goal of reducing the Gini score towards zero. On the other hand, should an agency wish to provide very high-quality transit service to a highly concentrated geographic area, a score moving towards a value of one would be the goal. In either sense, the framework provides a tool to measure distribution at several levels of aggregation.

Baltimore City and Washington, D.C., rank the highest in terms of transit connectivity inequality. The rankings on a GINI index such as this range from 0 for perfect equity to 1 for perfect inequity. Baltimore comes the closest to perfectly inequitable transit distribution with a score of 0.69. Prince George's County has the lowest inequity with a score of 0.48. While both Baltimore and D.C. have high inequity scores, the level of overall connectivity is quite high; indicating that there is a high-quality transit service in a centralized area, with less connectivity near households. In Prince George's, transit connectivity is much lower overall.

Table 5
Transit inequality index by location.

Location	Households	Connectivity	Gini's concentration ratio
Prince George's county, MD	298,412	0.03	0.48
Frederick, MD	80,687	0.00	0.51
Baltimore County, MD	316,330	0.23	0.51
Montgomery County, MD	352,228	0.08	0.64
District of Columbia	259,709	1.61	0.68
Baltimore City, MD	255,347	1.17	0.69
Maryland	2,128,042	0.18	0.83

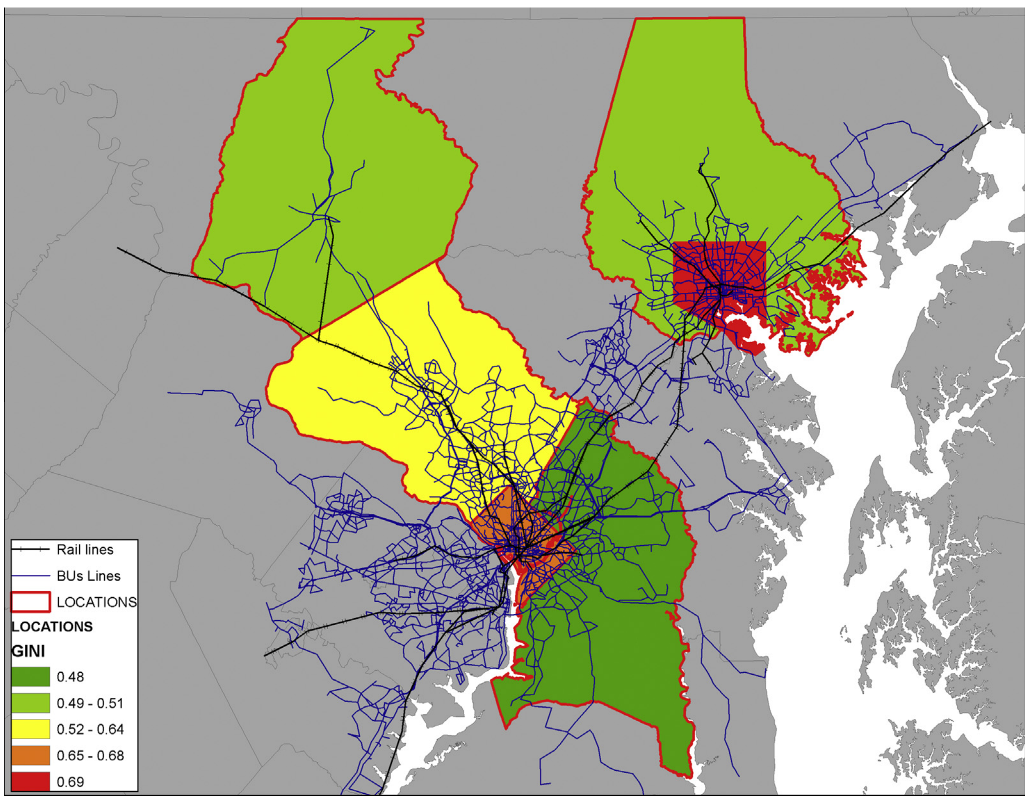

Fig. 8. Transit equity by location. *Source:* Created by Authors.

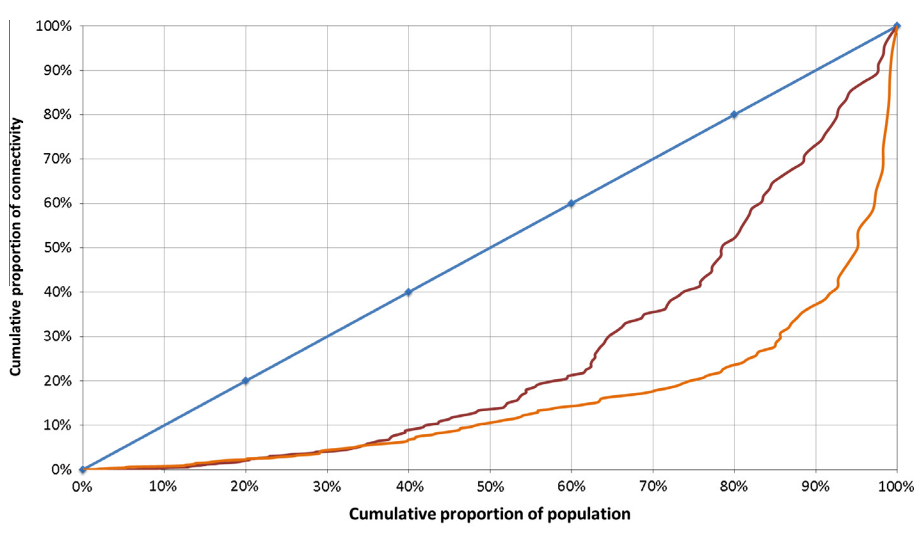

Fig. 9. Transit equity Lorenz curves. *Source:* Created by Authors.

However, the connectivity that does exist in the network is located in proximity to more households. Thus, the level of overall transit connectivity is not directly related to access to that system.

Fig. 8 provides a map of the transit equity results for each of the analysis locations. D.C. and Baltimore stand out with high Gini Index scores, due to the concentrated nature of connectivity in both cities. The typically suburban locations that surround the central cities have lower Gini Index scores, due to the decentralized nature of their transit networks in comparison to the highly centralized nature of transit in CBDs.

The equity analysis results can be represented as Lorenz curves to show how they deviate from a perfect equity line. Fig. 9 shows the Gini Index results for Baltimore City and Prince George's County. As the figure depicts, Prince George's has a much more equitable distribution of transit connectivity among households, with its Lorenz curve more closely aligned with the perfect equity line. The Baltimore City Lorenz curve shows how a greater portion of connectivity is accessible to a smaller portion of the city's households.

7. Summary and conclusion

This paper analyzes a methodology for transit equity estimation. Equity measures are often ignored in transit planning, despite federal mandates. A graph-theoretic approach considering equity and transit connectivity (following the major federal transit equity analysis criteria) has been presented. Equity, in this context, is a measure of the distribution of transit-service coverage to household and employment locations. Connectivity defines the level of coordination of the transit routes, coverage, schedule, speed, operational capacity, and urban form characteristics, and is an influential element of the quality of service for any transit network. A Gini index is incorporated into the graph theoretic approach to estimate transit equity. Two spectrums of the index can vary between 0 and 1. An equity value of "0" represents a perfectly equitable distribution of service and "1" represents a perfectly inequitable distribution. While these two extreme values for the inequity index generally do not occur among any population, it is desirable in many cases that the inequality value remain as close to zero as possible.

Analyzing transit equity is a complex task due to the intricacy of many interacting factors embedded in a multi-modal transit network encompassing various public transportation modes with different characteristics, such as buses, express buses, subways, light rail, metro rail, commuter, and regional rail. In addition, multimodal transit networks, like highway networks, consist of nodes and links. However, links in a multi-modal transit network have different characteristics from those in a highway network, as links in a multi-modal transit network are part of a transit line that serves a sequence of transit stops (nodes). A stop can be served by different transit lines, and multiple links may exist between nodes in a multi-modal transit network. The indicator development process is further complicated as connectivity varies by urban form, with differences among geographical, land use, highway, and trip-pattern characteristics between regions. The performance indicator should include all of the aforementioned complexities and should be quantified to measure the transit equity of the multi-modal transportation network.

We presented an example problem to demonstrate the concept developed in the methodology and the advantage of the proposed methodology. Finally, the methodology was applied to the Washington–Baltimore region and equity estimated for six counties. Maximum equity is achieved for Prince George's County, with minimum equity for Baltimore City. The higher inequity value for Baltimore City reflects the spatial distribution of employment, with the greatest concentration in the Central Business District (CBD) serviced by high levels of transit connectivity, whereas the surrounding area is not well connected by transit. In contrast, Prince George's County transit inequity is low, which shows that a CBD type of employment location is not a part of this county. Rather, the spatial distribution of job locations and the transit system is fairly even throughout most of the county. The proposed estimates are not designed to assert whether the existing transit systems are equitable or not, but to establish a framework to measure equity before and after proposed transit system changes. There are many cases where it may be perfectly desirable to have a lower initial transit equity value simply because of the built environment and existing CBD-style development. However, as federal policy dictates, changes in transit service should not reduce the equitable distribution of transit service. This paper provided a generalized and tractable method to determine if planned service changes comport with federal equity requirements.

In addition, the proposed tool can be used by transit agencies to measure the distribution of transit service among specific populations to provide better access to captive riders. Transit equity is essential to connect households to jobs and the major activity centers. The contribution of the paper, therefore, is three fold: first, it developed a methodology for transit equity estimation; second, it applied the methodology to demonstrate the proposed approach in a simplified example problem; and, third, it examined the multi-modal transit network equity in the Washington–Baltimore region. Future research should include additional required equity analysis items like fair prices to enhance the service indicator metrics.

Appendix A

Notation	Explanation
$P^i_{l,n}$	inbound connecting power of link l
$P^o_{l,n}$	outbound connecting power of link l
$P^t_{l,n}$	total connecting power of line l at node n
C_l	average vehicle capacity of line l
F_l	frequency on line l
S_R	set of stops in region R
D^i_l	inbound distance of link l
D^o_l	outbound distance of link l from node n to destination
$T_{l,n}$	transfer scaled index of node n in a line l
S_l	set of stops in line l
S_ω	set of stops in transfer center ω
S_σ	set of stops in region center σ
V_l	average speed of link l
n_0	initial stop
$t_{n_1,n}$	transfer time from n_1 to n
θ_{ZU}	connectivity index for a zone
$\rho_{n_1,n}$	passenger acceptance rate from node n_1 to n
ρ_R	density measure for region R
a	parameter for passenger acceptance rate
b	parameter for passenger acceptance which is sensitive to travel time
L	link
N	node
N	network system
P	node dependent on n
α	scaling factor coefficient for capacity of line l
β	scaling factor coefficient for speed of line l

Appendix A (*continued*)

Notation	Explanation
γ	scaling factor coefficient for distance of line l
λ	eigenvalue
$A_{l,n}$	activity density of line l, at node n
ϑ	scaling factor for activity density
$H^z_{l,n}$	number of households in zone z containing line l and node n
$E^z_{l,n}$	employment for zone z containing line l and node n
$\Theta^z_{l,n}$	area of z containing line l and node
Θ^n_l	number of lines l at node n
G_α	Gini index value for a population or sample α
X_k	cumulative proportion of the population endowed with attribute k (in this case transit connectivity) for $k = 0,\ldots,n$
Y_k	the cumulative proportion of attribute k

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