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Assessing public transit service equity using route-level accessibility measures and public data

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ABSTRACT

The benefits and burdens of public transit service changes can be quantified using many different metrics. In the United States, the Federal Transit Administration requires transit agencies to assess the equity of proposed service changes using the demographic shares of affected riders. The purpose of the work presented here is to inform the development of more robust transit equity analyses than are currently conducted by integrating measures of accessibility – the ease with destinations can be reached – into FTA-required analyses. The measures are calculated using publicly available data, including the US Census Bureau's Longitudinal Employer-Household Dynamics dataset and transit route and schedule information in the General Transit Feed Specification (GTFS) format. The results demonstrate that relying on a single measure (e.g. population shares or accessibility) to associate a route with a particular demographic group is likely to be deficient. Previous academic work on accessibility has not translated well to practice in part because the calculation of accessibility relied upon regional travel demand model outputs that were difficult to obtain. This work thus fills an important gap in the literature and practice by tying advances in the academic literature to FTA-mandated analysis with publicly available data.

1. Introduction

Achieving equity in the provision of public transit service has been a transportation policy goal in the US since at least the 1970s (e.g., Krumholz and Forester, 1990; Pucher, 1982). Differences in access to and accessibility by public transit according to geography and demographics have been extensively studied (e.g., Currie, 2010; Sanchez, 1999; Shen and Sanchez, 2005; Taylor and Ong, 1995). At the same time, changing urban forms and decentralizing employment have made automobile ownership a necessity in most areas across the US, reducing public transit's relevance for accessibility provision (Blumenberg and Manville, 2004; Blumenberg and Ong, 2001).

Despite transit's limitations, substantial public funds continue to be allocated to its construction and operation and disputes have routinely arisen between the transportation disadvantaged and more affluent populations regarding the types of systems that should be funded and built (Golub et al., 2013; Grengs, 2002). Additionally, access to reliable and affordable transportation options, whether public or private, is vital to ensuring the full participation of individuals in societies across the globe (Lucas, 2004, 2012). Achieving transportation equity requires addressing each of these concerns simultaneously, but barriers include issues of data availability, scale, and scope, the absence of standard methods of equity assessment, weak guidance from agencies on analytical methods, and disagreement over appropriate definitions (Karner and Niemeier, 2013; Lei et al., 2012; Martens, 2012; Rowangould et al., 2016; Sanchez et al., 2003; Truelove, 1993).

In the United States, the Federal Transit Administration (FTA) requires its fund recipients located in urbanized areas exceeding 200,000 in population to perform a service equity analysis whenever a "major service change" is undertaken (Federal Transit Administration, 2012a). The purpose of the analysis is to guard against discrimination in the distribution of federal funds, as required by Title VI of the 1964 Civil Rights Act (Federal Highway Administration, 2012; Federal Transit Administration, 2012a, 2012b). The goal of the service equity analysis is to determine whether a proposed change will have a disparate impact on racial minorities and/or place a disproportionate burden on low-income populations.

The analysis as prescribed is inherently spatial—it relies upon comparing the demographic shares of the population likely to be affected by a service change (e.g. the population living near affected transit stops or stations) to that in the greater service area. If the burdens of a service cut fall disproportionately on people of color or low-income or if the benefits of a service improvement accrue disproportionately to whiter and more affluent populations, a service

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change may be judged to be discriminatory.

Such an analysis is undoubtedly necessary, but the data and methods prescribed by FTA are limited (Karner and Golub, 2015); no consideration is given to changes in public transit accessibility or level of service. Yet for decades, transportation scholars have identified the ability to access destinations dispersed across space as the primary benefit conferred by a transportation system (e.g., Martens, 2012; Wachs and Kumagai, 1973). Work is needed to integrate methods, findings, and best practices from transportation geography into public agency practices. The purpose of this study is to inform the development of robust transit equity analyses, consistent with the spirit of FTA's prescribed methods. Specifically, indicators of accessibility and equity are developed and applied to the Phoenix, Arizona metropolitan area's multimodal transit system. In contrast to many prior measures, those developed here link together both the opportunities available at the destination end of a trip and the characteristics of employed residents located at the origins.

The results demonstrate how a service equity analysis could incorporate broader conceptions of accessibility and the consequences of relying on demographic approaches alone. Some routes with relatively low proportions of low-income riders, for example, evidence relatively high accessibility to low-wage jobs, meaning that the share of a route's ridership that is low-income is a relatively poor indicator of the substantive importance of a route to low-income people. Additionally, measures that consider where workers live as well as the location of suitable employment opportunities demonstrate greater equity than those that consider only the location of opportunities. These combined results suggest that relying on a single measure to associate routes with particular demographic groups is likely to be deficient.

The data and methods presented here are based on publicly available data in the US that, with minor modifications, could be used in other contexts to address transit equity-related questions. These data are being continuously updated, making it possible to track accessibility changes over short time periods. Previous academic work on accessibility has not engaged deeply with the types of service equity analyses that US transit agencies must conduct day-to-day. This work thus fills an important gap by tying advances in the academic literature to FTA-mandated analysis using publicly available data.

2. Literature and practice review

In the literature on transit ridership, two groups have been identified: choice and transit dependent riders (Garrett and Taylor, 1999; Grengs, 2005; Taylor and Morris, 2015). Choice riders typically have an automobile available but choose high-level-of-service transit modes during the commute (e.g., commuter rail or express bus). Transit dependents lack access to an automobile and must rely on transit, ridesharing, or other means to access desired destinations. Prior work has revealed important demographic differences between these two groups; namely, that transit dependent populations are more likely to be people of color and low-income than choice commuters (Garrett and Taylor, 1999). This market segmentation creates challenges for transit planners and civil rights enforcement. Without even considering the vast differences in accessibility afforded by the automobile versus public transit (Golub and Martens, 2014; Grengs, 2010), a single transit agency responsible for a multimodal system has to make choices regarding relative service levels subject to limited funding. Investing in choice modes and routes is seen as an important strategy to reduce congestion and vehicle-miles traveled, but can draw funding away from serving transit dependents. Recent history has seen a de-emphasis of transit dependents and re-emphasis on choice riders due to the vagaries of US transportation policy and finance and other political-economic factors (Grengs, 2005).

This shift in emphasis increases the likelihood that the civil rights of transit dependents will be violated. Appropriate care must be exercised to determine whether an equitable level of service is being provided to this population relative to choice riders. In the US context, under Title VI of the 1964 Civil Rights Act, agencies receiving federal funding cannot discriminate in the distribution of those funds. According to environmental justice guidance, those agencies must also avoid disproportionately burdening populations of color and low-income populations while ensuring that they receive a fair share of the benefits of federal investments (Marcantonio et al., 2017). Measuring discrimination and disproportionality is challenging. How they are operationalized can determine whether and the extent to which problems are identified (Rowangould et al., 2016; Talen and Anselin, 1998; Truelove, 1993). Regulations and other guidance promulgated by executive agencies seek to provide structure to such analyses.

FTA has produced guidance aimed at determining whether the distribution of benefits and burdens resulting from proposed fare and service changes are equitable (Federal Transit Administration, 2012a). For the service equity analysis, a public transit agency establishes the demographics of their entire service area (i.e. shares of specific groups) as a basis for comparing the demographic shares of those routes affected by a service change (either a cut or addition). If the share of people of color or low-income people in the total affected population facing a service cut is substantially greater than that in the overall service area, the proposed service change may need to be altered or abandoned (e.g., CDM Smith et al., 2014; Los Angeles County Metropolitan Transportation Authority, 2013). The opposite is true for service improvements.

Although the methods prescribed by FTA for this analysis are very specific (see, e.g., Federal Transit Administration, 2012c, 2018), they are based entirely on rider demographics. FTA's guidance does not recommend or endorse the use of measures of service quality, including travel time, accessibility, or rider comfort, which may be more meaningful indicators of transit system performance and equity than proximity or demographics.

The literature on public transit equity offers some guidance for the selection of superior measures. There is a substantial body of work related to transit equity that quantifies a measure of transit supply in relation to demand as captured by population demographics. The goal of these studies is to determine whether areas that experience concentrated disadvantage have either adequate access to transit service or have equitable transit service relative to areas that are not disadvantaged. In other words, it seeks to determine whether there is a “needs gap” between populations likely to use public transit and transit service (Currie, 2004). Typical studies in this tradition employ transit supply measures based on available data and demographics as a proxy for transit demand. Commonly employed measures of supply operationalize access to the transit system using one or more measures calculated for a small geographic area, including, for example, average proximity to transit stops, average headway, service coverage, and network density (e.g., Al Mamun and Lownes, 2011; Currie, 2010; Mavoa et al., 2012; Minocha et al., 2008; Wu and Hine, 2003).

Although they are often straightforward to calculate, such measures of access to the system tell us little about how well transit links people to destinations. For this reason, measures of accessibility are generally preferred. Indeed, accessibility – the ease with which destinations can be reached for a given transportation-land use configuration – has been identified as a fundamental metric of transportation system performance (Golub and Martens, 2014; Grengs, 2015a; Martens, 2012). Accordingly, it has seen widespread application in both the literature and practice of transportation equity analysis (e.g., Páez et al., 2010; SCAG, 2012) and is an ideal measure upon which to base a public transit equity evaluation. Calculating true accessibility requires linking measures of the opportunities available across space (e.g. employment, healthy food, education) with general measures of travel cost. Because of the importance of employment to well-being, job accessibility is commonly used (e.g., Golub and Martens, 2014; Hu, 2015; Manaugh and El-Geneidy, 2012). When assessing the employment accessibility landscape faced by different demographic groups, it is important to use measures of jobs that are appropriately matched to that group; measures of accessibility to total jobs, for example, may give different results than those that are disaggregated by wage level (Manaugh and El-Geneidy, 2012).

Studies that employ true accessibility measures to assess public transit equity have often relied on relatively coarse spatial scales and public transit travel times derived from regional travel demand model skims calculated at the transportation analysis zone (TAZ) level (e.g., Currie, 2004; Grengs, 2015b; Shen, 2001). In the typical analysis, travel times are obtained between TAZs and the attractiveness of destinations is quantified at the same scale. Temporal resolution is also aggregate, relying on a single TAZ-TAZ skim meant to represent average service over time periods spanning several hours or more (Farber et al., 2014; Lei et al., 2012). Later work incorporated more spatially and temporally explicit measures of transit supply into accessibility research, determining, for example, how access by transit to healthy foods changes over the course of a day (Farber et al., 2014) or making national-level comparative assessments of transit service availability using consistent data sources (Owen and Levinson, 2014; Tomer et al., 2011). This dramatic improvement has been made possible by the increasing availability of data in the general transit feed specification (GTFS) format. These data provide reliable, current, and highly detailed information on public transit routes, stops, and frequencies for an individual operator in a standard format. They can be used to create metrics that more closely reflect the actual experiences of individuals that rely on public transit.

Clearly, many attempts have been made to quantify public transit needs gaps and accessibility, but few put forward standards for assessing whether a particular set of investments or state of affairs is equitable. Importantly, the literature has thus far engaged very little, if at all, with FTA-required service equity analyses. The goal of the present study is to address these previous shortcomings by developing and demonstrating a measure of public transit accessibility that can be applied for transit planning purposes and during federally required service equity analyses. The analysis is motivated in part by the observed shift in broad public transit funding patterns that benefit choice riders at the expense of transit dependents. The measures developed here can be used to provide a direct comparison of accessibility outcomes for protected demographic groups (e.g. low-income workers) relative to a system-wide mean or non-protected groups (e.g. high-income workers). Rather than determining whether supply and demand are well-matched, as in the needs gap studies, it quantifies the accessibility afforded to each group at the level of a transit route, which provides a direct link to FTA's requirements and actionable information for transit planners.

3. Methods and data

Fundamentally, accessibility measures combine estimates of mobility (travel time, cost, or distance) with land use characteristics. For the latter, common measures include counts of spatially dispersed opportunities (number of jobs, shops, or services) or distances to the nearest location of a certain type. For this paper, we employed data from OpenStreetMap, Valley Metro's GTFS feed, and the US Census Longitudinal Employer-Household Dynamics (LEHD) Origin-Destination Employment Statistics dataset for the Phoenix metropolitan region. A key component of the methods involved software developed by the Environmental Systems Research Institute (ESRI, a commercial organization) that allows GTFS data to be added to a traditional ArcGIS network dataset and included in network analyses (Morang, 2014). This innovation facilitates the calculation of highly disaggregate, temporally specific public transit travel times and has previously been applied to answer accessibility-related questions (Farber and Fu, 2017; Farber et al., 2014; Fransen et al., 2015).

Calculating the accessibility metric employed here began with the creation of a multimodal network dataset in ArcGIS to represent pedestrian facilities in the Phoenix metropolitan region. A reasonable approximation can be obtained by exporting data for an entire urban area from OpenStreetMap and deleting limited-access freeway links and barriers to automobile travel that can be circumvented on foot. Once built, the pedestrian network can be used to generate service areas (i.e. buffer zones representing actual walking distances along the pedestrian network) around transit stops and stations. The standard FTA approach recommends Euclidian buffers of 1/4 mile around bus stops and 1/2 mile around rail stations (Federal Transit Administration, 2012a). Using service areas instead of buffers will better represent the demographics and opportunities actually reachable within the specified distances.

Resident worker and job characteristics for each service area were subsequently aggregated using the LEHD for 2011. The LEHD provides block-level estimates of resident workers, jobs, and flows of resident workers to jobs for the vast majority of areas in the United States. If these demographic and employment counts were simply joined directly to service areas, substantial double counting would result when calculating accessibility metrics. It was therefore necessary to undertake a number of operations to ensure that employment opportunities were only counted once. The procedure used was as follows. First, all service area polygons were split into their component lines and then recombined into non-overlapping shapes, while maintaining their association to individual stops. These combined operations resulted in the creation of a large number of "slivers." Census block centroids falling within a service area sliver had their demographic and employment counts associated with them. This process ensures that all residences and employment located within the previously defined service areas will be included in the accessibility calculations and that stops can be uniquely associated with routes. Because census blocks are already the smallest available unit of geography, this approach was judged to be superior to areal interpolation. The LEHD provides many job and resident worker categories, including wage-level, race/ethnicity, and job type. For this analysis we used resident worker and job locations for the three wage categories: low-wage (less than \$1250 per month), mid-wage (\$1251–\$3333 per month), and high-wage (greater than \$3333 per month).

Travel times by public transit between origins (each transit stop) and destinations (all service area slivers) were calculated using standard ArcGIS network analysis approaches and the ESRI GTFS add-in. Walking could occur along the street network for access, transfer (if required), and egress. A walking speed of 5 km/h was assumed. We estimated travel times for departures occurring during a two-hour peak period (7:00–9:00 AM), as defined by the Maricopa Association of Governments, the metropolitan planning organization for the Phoenix metropolitan region (Maricopa Association of Governments, 2012). Specifically, travel times were generated representing a random departure during each of the 24 five-minute periods comprising the peak. The mean travel time evidenced during this period was considered to be representative, consistent with other accessibility studies (Farber and Fu, 2017; Owen and Levinson, 2015). Alternative measures are possible, for example, in locations where transit users can reasonably be expected to be familiar with the transit schedule, the minimum travel time might be more appropriate since they will be able to to minimize their initial wait time and/or transfer times. Only travel times less than 64.1 min were considered, making the computation tractable. This threshold captures approximately 95% of all trips taken during the 2010–2011 on-board survey conducted for Valley Metro (ETC Institute, 2011).

With demographics and travel times calculated, it was possible to develop accessibility measures. We used two versions of the familiar gravity model formulation of accessibility:

$$AT_i^w = \sum_j E_j^w e^{-\beta t_{ij}} \tag{1}$$

$$AW_i^w = W_i^w \frac{AT_i^w - \overline{AT^w}}{\sigma_{AT^w}} \tag{2}$$

where

AT_i^w = Territorial accessibility at stop i for resident workers with wage level w

AW_i^w = Worker − weighted accessibility at stop i for resident workers with wage level w

E_j^w = Jobs in service area sliver j with wage level w

W_i^w = Resident workers in service area at stop i with wage level w

$\overline{AT^w}$ = Mean territorial accessibility for resident workers with wage level w

σ_{AT^w} = Standard deviation of territorial accessibility for resident workers with wage level w

t_{ij} = Average peak period travel time (minutes) by transit between stop i and service area sliver j

β = empirically derived impedence term

i indexes the entire set of 7445 transit stops in the Valley Metro system, j indexes the 4821 service area slivers containing employment, and w indexes wage levels in the three LEHD categories. In addition to the accessibility values for each wage category calculated with Eq. (1), summing over all three categories provides an indication of the total, or overall, accessibility for a transit stop. By explicitly representing the entire transit trip and modeling the pedestrian environment at the transit stop level, the correspondence between these measures and the actual experience of taking public transit will be more closely aligned than if travel demand model outputs representing travel times between TAZ centroids were used for the same purpose.

The impedance term was derived using ridership information from the 2010–2011 Valley Metro on-board survey (ETC Institute, 2011). That dataset contained geocoded boarding and alighting locations. Travel times for each home-based work trip were determined as the mean travel time over the departure hour using the GIS approaches described above, and the empirical trip-length frequency distribution was derived (Fig. 1). In contrast to the lognormal distribution typically evidenced for automobile travel, the distribution of transit travel times is relatively more normal and indicates a much less rapid decay than is typically found for auto (e.g., Ortúzar and Willumsen, 2001, p. 173). Because of this revealed behavior, we set the impedance term to zero for jobs accessible within the mean travel time (39.9 min) and estimated it at 0.049 using nonlinear least squares for those jobs further than mean travel time. We subtracted the mean from travel times that exceeded it before use in Eqs. (1) and (2). This approach to impedance is similar to assuming that transit users have a "built in" expectation of the minimum length of a trip. Their propensity to travel by transit only decreases once this length is exceeded. Conceptually, this approach is a hybrid of a cumulative opportunity and gravity measure of accessibility; all opportunities within the threshold are weighted equally, but those further than the threshold are discounted. Improvements in transit service would bring more opportunities within and beyond the threshold distance, increasing accessibility. A similar approach was used by Hu (2015) in an accessibility analysis conducted for Los Angeles, CA.

The measure defined in Eq. (1) (referred to as "territorial" accessibility) totals available opportunities from each origin, regardless of the characteristics of individuals at that origin. Such territorial measures applied in areas with high rates of automobile dependence (e.g., Canada, the United States, and Australia) typically result in high values in

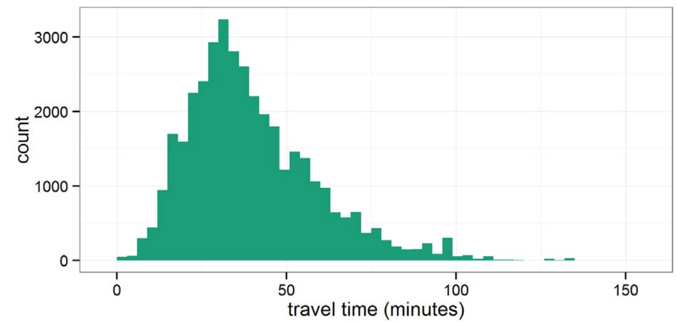

Fig. 1. Trip length frequency distribution for all walk plus public transit home-based work trips in the 2010–2011 Valley Metro origin-destination survey.

central city areas, where transit service is concentrated. Because disadvantaged populations have historically been disproportionately concentrated in these areas as well, supply and demand often appear to be well-matched by this measure (e.g., Delbosc and Currie, 2011; El-Geneidy et al., 2016). But proportions tell us little about the actual number of persons that experience a given level of accessibility.

The measure defined in Eq. (2) (referred to as "worker-weighted" accessibility) addresses this problem by explicitly including the number employed residents living within each service area (by wage category) into the calculation as a weight.[1] If no employed residents of a particular wage category live within the service area of a transit stop, that stop will be assigned an accessibility value of zero using Eq. (2). Its employment (if any) will still contribute to the accessibility values calculated for other stops. We standardize the territorial accessibility measure before weighting to ensure that high scores reflect situations where many workers reside in areas of high accessibility. Locations with many workers but low accessibility would score poorly. The worker-weighted approach also embeds the attractive property that substantively larger values of accessibility correspond to larger numbers of jobs and resident workers nearby, in contrast to competitive accessibility measures (e.g., Shen, 1998).

Because each service area sliver is associated with the stop from which it was generated, both measures can be used in conjunction with appropriate queries of a GTFS feed to aggregate accessibility information over all stops that belong to a route. The result is route-level measures that can be directly employed in transit service equity analyses.

4. Results and discussion

4.1. Proximity to transit

According to the LEHD, there were approximately 1.7 million total jobs and 1.65 million resident workers in the Phoenix-Mesa-Glendale Metropolitan Statistical Area (MSA) in 2011. The total number of resident workers and jobs in each wage category, along with those captured within a 1/4 mile network walking distance of a bus stop or a 1/2 mile network walking distance of a rail station are shown in Table 1. The table shows that about 22% of the region's workers live within a reasonable walking distance of transit and that 45% of the region's jobs are within walking distance of transit. It also shows that both low-wage and mid-wage employed residents are more likely to be located near to transit than high-wage resident workers. This finding is sensible, as higher wage workers are likely to prefer locations on the periphery of the region, where per unit housing costs will be lower.

Although Table 1's aggregate, buffer-level analysis can provide a rapid diagnostic of transit service equity, simply having access to the

[1] Other weights could be used to address different equity-related questions, including the number of working age or unemployed people.

Table 1
Valley Metro Service Coverage by LEHD Wage Level.
Sources: Valley Metro GTFS Feed, 2011 LEHD dataset.

	Phoenix-Mesa-Scottsdale MSA total		within pedestrian buffer of transit (percent of total)	
	Resident workers	Jobs	Resident workers	Jobs
Low-wage	403,318	421,384	95,805 (24%)	189,878 (45%)
Mid-wage	635,428	661,529	162,480 (26%)	298,744 (45%)
High-wage	701,665	718,117	129,602 (18%)	323,033 (45%)
Total	1,740,411	1,801,030	387,887 (22%)	811,655 (45%)

public transportation system by proximity to a stop is not a measure of accessibility. Although a particular job may be covered by a pedestrian buffer, that job can be effectively inaccessible if it is only served by a route that runs at an inconvenient time for the traveler that needs to access it. The proximity-based analysis is therefore unlikely to reflect the utility of the transit system for individual users or trips. The remainder of this discussion therefore focuses on the accessibility provided by individual transit stops and routes in the system.

4.2. Modeled accessibility

Fig. 2 shows the results of calculating stop-level gravity measures of accessibility to both low-and high-wage jobs using Eqs. (1) and (2). The wage groups were selected to provide maximum differentiation and the map is intended to illustrate broad spatial patterns and differences between the metrics, rather than a precise summary of the conditions at a particular location. Because the stops overlap substantially, the figure is summarized at the census block group level. Plotted values represent the mean accessibility for stops located within a block group and are grouped by quintile in each case, facilitating comparisons between measures. The top row of the figure shows the territorial accessibility to jobs by wage category (Eq. (1)). The results differ substantially by wage level. For low-wage jobs, the highest accessibility block groups are concentrated in central Phoenix, Tempe, and south Scottsdale. For high-wage jobs, there are highly accessible areas in central Phoenix, but the landscape of accessibility shifts northward to a much greater extent than it does for low-wage jobs. In both cases, accessibility tends to decrease the further one moves from these central areas. These results are not surprising; transit systems are built to connect areas of dense economic opportunities. They indicate that the geography of economic opportunity in the metropolitan region differs by wage level.

By only considering the location of jobs and travel times between origins and destinations, the territorial measure misses a vitally important aspect of transit accessibility – the locations of workers that require access to those jobs or to the services that they represent. Because of the historical propensity of disadvantaged populations to spatially concentrate in US central cities (e.g., Massey and Denton, 1993; Wilson, 1990), it will often appear as though disadvantaged populations enjoy high accessibility. But this comparison relies only on the share of disadvantaged residents in each location. In extreme cases, locations of high territorial accessibility might be completely mismatched with the residential locations of the population in terms of their total numbers. The bottom row of Fig. 2 addresses this limitation by weighting the territorial measure by the number of employed residents in each wage category within the service area of each stop (Eq. (2)). The results show a much more varied pattern of accessibility throughout the region that differs based on wage level.

For both wage groups, clear differences are apparent between worker-weighted and territorial accessibility formulations although there is still substantial overlap in the areas of highest accessibility for both wage levels. The most striking finding is that the areas of lowest accessibility located at the fringes of the region when using the territorial formulation appear to have greater accessibility when the worker-

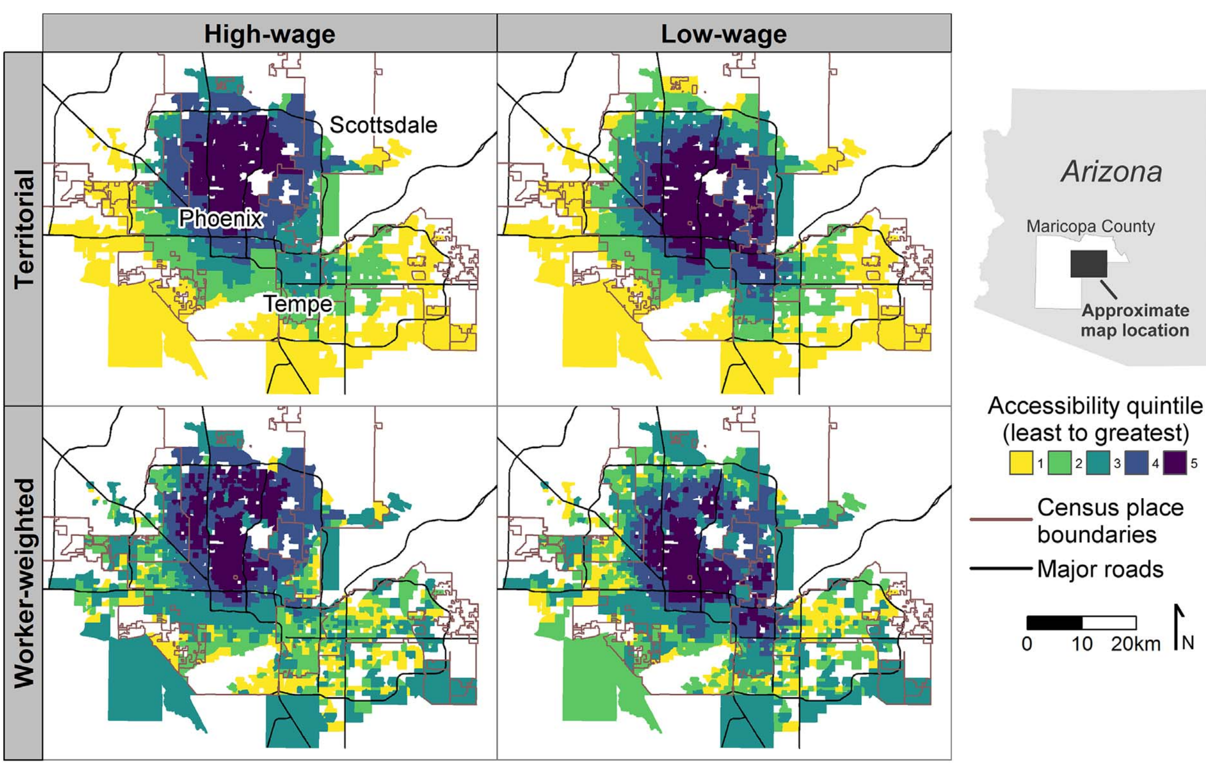

Fig. 2. Spatial distribution of stop-level gravity accessibility in the Valley Metro service area for two formulations: a) Jobs accessible from each origin transit stop (territorial accessibility, Eq. (1)) and b) Jobs accessible from each origin transit stop standardized and weighted by the total number of resident workers in the service area around that stop (worker-weighted, Eq. (2)). Results shown separately for accessibility to low- and high-wage jobs. Plotted categories of accessibility are grouped by quintile and stop-level results are aggregated to the block group for visualization purposes. Darker shades indicate higher values of accessibility. Major roads and geographic boundaries for census places are also shown.

weighted formulation is used. This result indicates that the total numbers of employed residents living far from employment centers is significant. The trip-making patterns and actual transit travel times in areas that switch from low to higher quintiles when moving from the territorial to the worker-weighted metric could be investigated with the goal of providing improved transit service, especially in the low-wage case. Differences between the two measures are also affected by the availability of affordable housing near job centers (e.g., Benner and Karner, 2016) and by the spatial distribution of amenities that affect residential location choice (e.g. school quality). On the other hand, areas that remain in the highest quintiles using both Eqs. (1) and (2) indicate locations where supply and demand are well-matched. By bringing the important element of transit demand into the accessibility formulation, Eq. (2) appears to provide a more nuanced and potentially more useful view of transit system utility than Eq. (1).

Spatial summaries of accessibility results like those shown in Fig. 2 are difficult to interpret in the context of transit service equity and generally require further disaggregation or summarization to be made meaningful. One disaggregate summary unit that has not been previously analyzed in the literature but which is of obvious relevance to public transportation and FTA-required analyses is the transit route. Although the trip is the fundamental unit of the GTFS feed, defined as one-way travel by a transit vehicle to visit specific stops at specific times, it is possible to identify all stops that are associated with a route at least once during a typical weekday run.

For each transit route, Fig. 3 shows the mean value of accessibility (Eq. (1)) along all associated stops. Results are again presented for the two wage categories expected to be most different – low and high. The accessibility values presented in the remainder of this paper are standardized within categories to facilitate comparisons across wage groups and because the total number of jobs in each group differs (Table 1). A point is plotted for each of the 102 routes in the Valley Metro system, simultaneously indicating the route's accessibility to high-wage and low-wage jobs. Both a 1:1 line (solid) and one standard deviation (dashed lines) in both directions from that line are also shown. Deviations from the 1:1 line would indicate that a route provides differing levels of accessibility to jobs at each wage level.

In this case, the results reveal that most routes provide relatively similar accessibility to jobs in both wage categories (Fig. 3). Because the calculated travel times include the possibility of transfers and also allow walking between stops and to destination service areas, the results should not be interpreted as representing a pure accessibility for an individual route. To the extent that travel times are shortest along a route, the measures will capture accessible job opportunities proximate to it; however, in areas with high job density, off-route opportunities will also be captured in the accessibility measure. This is not necessarily a problem, since a public transit system should function as an integrated, cohesive unit, linking people to opportunities located throughout the entire network, rather than along a single route.

Both the diagnostic utility of the route-level metric and its integrated nature are apparent in several of the outlier routes identified in the figure. In general, most routes provide relatively similar accessibility to low- and high-wage groups and low-wage accessibility is more closely grouped around the mean than high-wage accessibility. Some routes do provide disproportionate accessibility to one group or the other. Specifically, neighborhood circulators operating in areas with high concentrations of low-wage jobs in South Scottsdale and Tempe comprise the cluster of “low-wage outliers” identified in Fig. 3. All “high-wage outliers” are bus routes located in North Phoenix, where the highest quintile of high-wage territorial accessibility is observed and spreads out along the east-west axis. Importantly, because these results represent means, routes that operate entirely or mostly in areas with high job density will score highly. Routes that cross areas of low jobs density will be penalized. Valley Metro's light rail, for example, provides somewhat higher accessibility to low-wage than high-wage jobs, but despite its peak period service frequency (12 min), it is not the line that provides the highest accessibility to high-wage jobs. This is likely due to its passage between Phoenix and Tempe which contains very low job density. Many of the other routes that have higher accessibility to high wage jobs are near the light rail alignment, but have a shorter total length. Because of the accessibility formulation used here, where jobs reachable within the mean observed travel time (39.9 min) are weighted equally, jobs located within a reasonable walking distance or short transit trips can benefit the accessibility of nearby lines.

One limitation of Fig. 3 is that the accessibility measures only reflect the locations of jobs, not workers. To provide a measure of accessibility linked to transit demand, Fig. 4 uses Eq. (2) to again compare accessibility to low-wage and high-wage jobs. In contrast to Fig. 3, Fig. 4 shows many fewer routes providing disproportionate accessibility to one of the two wage groups. Most routes plot within one standard deviation of equitable service. Additionally, the dominant nature of light rail's accessibility provision becomes clear with the worker-weighted metric. In terms of overall accessibility, it is an obvious outlier, providing by far the greatest accessibility of all the routes for workers across the earnings spectrum. Four routes provide relatively more accessibility for high-wage workers; all four are also outliers in Fig. 3. Again, all operate in the high-wage jobs-rich area of North Phoenix. The results indicate that these specific routes traverse areas that are not only

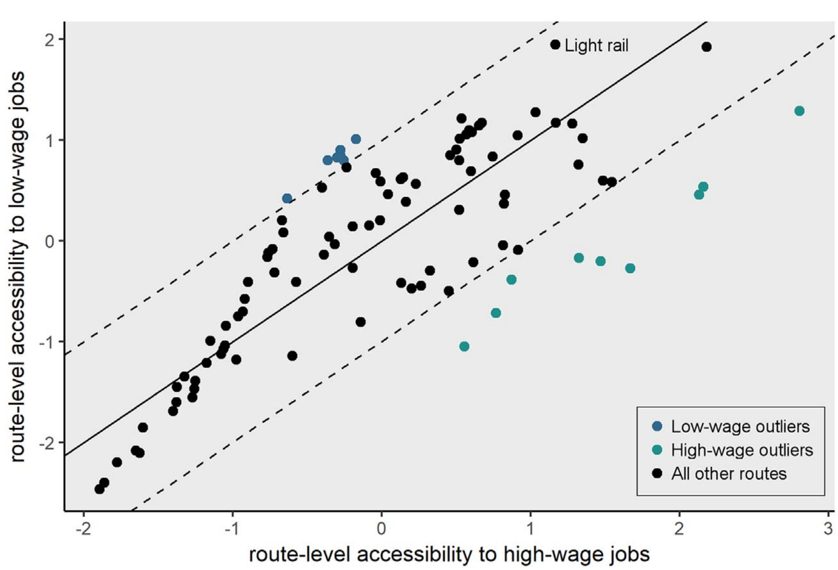

Fig. 3. Pairwise comparison of standardized gravity accessibility for low-wage and high-wage jobs (calculated using Eq. (1)). Each plotted point represents one route; its location is determined by the low-wage accessibility (y-axis) and high-wage accessibility (x-axis). Outliers identified and 1:1 line shown for reference.

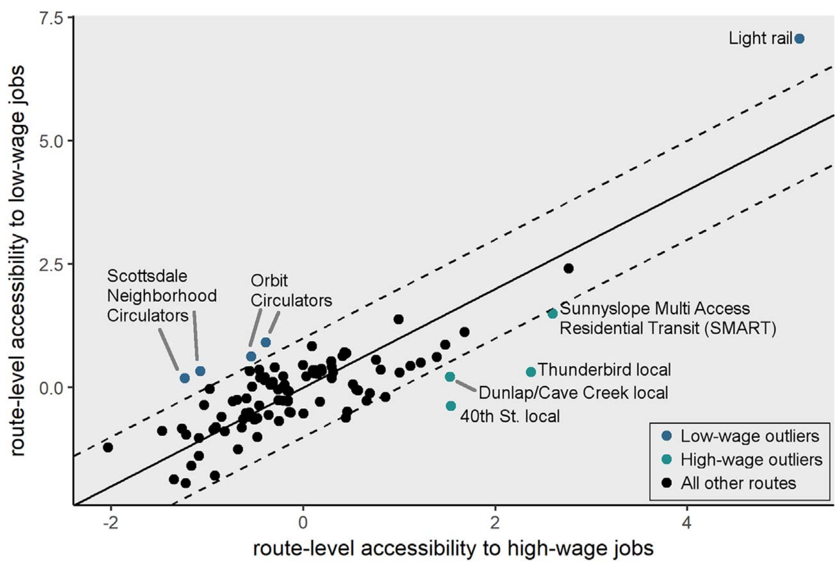

Fig. 4. Pairwise comparison of standardized gravity accessibility for low-wage and high-wage jobs (calculated using Eq. (2)). Each plotted point represents one route; its location is determined by the low-wage accessibility (y-axis) and high-wage accessibility (x-axis). Outliers labeled and 1:1 line shown for reference.

home to high-wage jobs, but that high concentrations of relatively affluent workers live within walking distance of their stops. The remaining four circulator routes identified in Fig. 4 are the same or similar to those identified in Fig. 3. In connecting low-wage jobs with high concentrations of low-wage people, they are likely to be of particular importance to that demographic group. The combined results demonstrate that the distribution of workers across a region can change the apparent accessibility provided by a route when using different accessibility formulations. Valley Metro's existing system appears more equitable once this distribution is taken into account, meaning that both low- and high-wage workers derive potential benefits from the accessibility provided by routes that score highly on territorial accessibility for one group or the other.

Figs. 3 and 4 demonstrate one way in which accessibility could be integrated into FTA-required equity analyses when service changes are undertaken. When proposing a change to existing service, a transit agency could use similar figures to determine whether routes proposed for cuts provide disproportionate benefits to low-income groups. Such cuts would be particularly detrimental to low-income populations regardless of whether protected populations comprise a large share of the overall ridership. Conversely, service improvements that disproportionately accrue to routes identified as high-income outliers may need to be balanced with improvements elsewhere. If data or staff capacity are available, underlying GTFS feeds could be updated to reflect proposed changes and shifts in the positions of routes in the equity figures quantified (e.g., Farber and Fu, 2017). Net changes in accessibility gains and losses could be computed and compared to ensure that the benefits/burdens do not accrue disproportionately to particular demographic groups. Quantifying the accessibility of routes in this way is one approach to developing a robust transit service equity analysis that incorporates accessibility and is consistent with FTA's method that emphasizes route-level changes.

4.3. Comparing accessibility and demographic shares

By quantifying accessibility at the route level, the methods developed in this paper lend themselves well to FTA's required service equity analysis (Federal Transit Administration, 2012a, 2012b). Presently, service equity analysis relies exclusively on comparing the demographics of routes slated to receive service changes to system-wide demographics (Karner and Golub, 2015). While important, demographic measures alone do not indicate how well particular routes connect populations to opportunities they would like to reach. Without a simultaneous accessibility analysis, transit agencies run the risk of justifying service cuts or expansions without considering the effect of those changes on the ability of residents to reach important destinations.

To investigate the utility of an accessibility metric for service equity analysis, Fig. 5 compares a typical metric used in FTA analyses (e.g., Los Angeles County Metropolitan Transportation Authority, 2013) – share of boardings by low-income passengers by route – to the worker-weighted accessibility metric calculated using Eq. (2). The figure classifies routes into either low-income or non-low-income based on the proportion of boardings made by low-income passengers. According to Valley Metro's most recent on-board survey, 34% of all system boardings are individuals with household income less than $15,000 per year (ETC Institute, 2011). This threshold precisely matches the LEHD's low-wage category (< $1250 per month). Accordingly, routes classified as low-income in Fig. 5 are those with greater than 34% of boardings attributable to low-income riders. As can be seen from the figure, many routes that would not be considered low-income by the transit agency are clearly of importance to low-wage travelers because they provide high accessibility to low-wage jobs. In fact, 19 out of 34 of the non-low-income routes as measured by transit boardings provide greater than median accessibility for low-wage workers to low-wage jobs. The figure highlights one weakness of relying exclusively on demographic shares to determine the equity impacts of transit decisions: ridership shares miss important information about the accessibility provided by and relative importance of different transit lines. When considering potential service changes to these routes, the standard analysis might find no

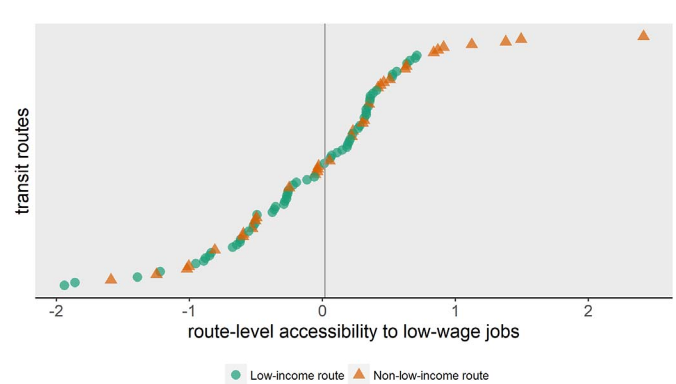

Fig. 5. Route-level transit ridership compared to route-level accessibility to low wage jobs (calculated using Eq. (2)). The vertical line represents median accessibility. To preserve the x-axis scale, the value for light rail has not been plotted.

evidence of a potentially harmful outcome based on demographics when one would almost certainly emerge due to the damage done to low-wage accessibility.

The integration of an accessibility perspective into FTA analyses would ideally supplement, not replace, the existing approach based on demographic shares. This point is particularly important to emphasize, because routes with seemingly low accessibility could be providing vitally important lifeline connectivity to essential services like health-care or education. Transit agencies routinely seek to balance the fiscal imperative to provide revenue-generating service with the social need to provide adequate coverage for transit dependent populations (Walker, 2012, pp. 117 ff.). The purpose of the present study was to demonstrate how emerging, publicly available datasets can be used to generate accessibility measures that can inform more robust analyses of public transit service equity than are currently conducted. Using these measures to supplement FTA-required analyses would begin to ensure that routes providing strong connectivity for low-income populations do not slip through the cracks when analyses are conducted simply because their demographic shares do not categorize them as "low-income."

5. Conclusions

Analyzing public transit accessibility has historically been the province of regional transportation planning agencies through the use of four-step or activity-based travel demand models. These models require staff or consultant time to operate and maintain, require specialized and expensive software, and take substantial time to complete a single run. Academic research has often relied on the provision of coarse skims derived from these regional models and the goodwill of planning staff to provide them. The spatial and temporal resolution of a four-step model presents serious barriers for detailed accessibility analysis. Travel times by transit are typically represented between two zonal centroids as a representative average over a period that spans several hours.

The work presented in this paper builds upon prior research showing that publicly available data sources and commonly available proprietary software can provide measures of public transit accessibility calculated with high spatial resolution. These measures can subsequently be linked to route-level indicators and used to comply with the spirit of FTA's service equity analysis recommendations. The indicators developed here go beyond assessing the demographics of transit riders to include full consideration of public transit's ability to link potential passengers to employment opportunities. This type of analysis is consistent with best practices derived from the transportation literature and can provide additional information when an initial finding shows there to be no disparate impact or disproportionate burden on protected populations. A key finding is that a route identified as low- or high-income using territorial measures or demographic shares alone may actually be substantively important to the other group, once the location of resident workers is taken into account. Assessing multiple measures and definitions when conducing an equity analysis can help to ensure that the results are judged meaningful by the populations the analysis is meant to protect (Karner, 2016; Karner and London, 2014; Karner and Niemeier, 2013; Rowangould et al., 2016).

Despite the technical advances developed in this paper, the methods contain limitations that should be considered when interpreting the results. Specifically, modeled trips include walking, waiting, and in-vehicle time, but those three components cannot be disaggregated. This means that, in some cases, the accessibility results are more likely to reflect the experiences of pedestrians than transit patrons. We also used a single service area definition, depending on mode, to reflect the pedestrian-shed for individual stops and stations. It is likely that different transit users and demographic groups are willing to walk different distances to transit and that this will have implications for accessibility assessment. Despite these limitations, integrating measures of transit level of service into service equity analysis practice can help to ensure that proposed service changes do not inadvertently burden protected populations.

Many promising areas for future work flow from the research presented in this paper. One obvious extension is to use the methods developed for transit system planning. By operationalizing accessibility at the stop level, we have developed the potential to identify areas where improved service would maximize accessibility benefits for disadvantaged populations. Work in this vein could simulate changes to stops or routes using updated GTFS feeds and identify concomitant changes in accessibility, using variations on Figs. 3 and 4. The results could be used to supplement and/or inform the opinions of transit planners or members of the public. Another extension would involve analyzing other types of trips. Although the AM commute trip is important, transit dependent populations rely on the system for meeting many other daily needs as well. Serving non-work travel needs is therefore an important function of any public transit system. Additionally, the LEHD contain a wealth of information on employees (e.g. race/ethnicity, educational attainment) and workplaces (industry classification, total employment, number of years operating) that could be incorporated to assess different types of accessibilities for different groups and places.

Keeping public transit functioning well for those most likely to use it and improving it such that it becomes a more attractive option for drivers are both vitally important sustainability strategies. Understanding the equity-related tradeoffs and synergies inherent in both strategies is vital, but requires meaningful data and robust tools. The results presented herein are offered as a step toward their joint development.

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