Development of highly resolved spatial and temporal metrics of public transit accessibility
and their application to service equity analysis

Alex Karner
Julie Ann Wrigley Global Institute of Sustainability
Arizona State University
1151 S. Forest Ave.
Tempe, AZ  85218
510-725-4285
alex.karner@asu.edu

Word count

Words = 5,714
Figures (6 @ 250) = 1,500
Tables (1 @ 250) = 250
Total = 7,464
ABSTRACT

Determining whether a public transit network provides equitable accessibility to different population segments is an ongoing challenge. The purpose of this work is to inform the development of more robust transit equity analyses than are currently conducted. To this end, we develop and demonstrate the utility of a highly spatially and temporally resolved accessibility indicator with an application to the Phoenix, Arizona metropolitan area’s multimodal transit system. The indicator is 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. This measure has clear application to the service equity analyses required of the Federal Transit Administration’s (FTA) fund recipients. 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.
INTRODUCTION

Achieving equity in the provision of public transit service has been an ongoing challenge in the US since at least the 1970s (1, 2). Differences in access to and accessibility by public transit according to geography and demographics have been extensively studied (3-5). At the same time, changing urban forms and decentralizing employment have made automobile ownership a necessity in many areas, reducing public transit’s relevance for accessibility. Barriers to achieving transit equity include issues of data availability, scale, and scope, the absence of standard methods of equity assessment, and disagreement over appropriate definitions (6-9).

The legal basis for transit equity in the US obtains from the 14th Amendment to the Constitution, and Title VI of the 1964 Civil Rights Act. Recipients of federal funds are prohibited from discriminating in their distribution of that funding. To protect against such discrimination, 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 (10). The analysis is intended to determine whether a proposed change will have a disparate impact on racial minorities and or place a disproportionate burden on low-income populations.

FTA prescribes the use of very specific methods for the service equity analysis (see, e.g., 11, 12). Although the methods are specific, they are based entirely on the demographics a) proximate to transit systems or b) of observed ridership. FTA’s methods do not include measures of service quality which may be more important indicators of transit system performance and equity than proximity or rider demographics. This paper proposes a highly spatially and temporally resolved accessibility indicator and demonstrates its utility with an application to the Phoenix, Arizona metropolitan area’s multimodal transit system. This measure has clear applications to FTA-required equity analysis.

The purpose of this work is to inform the development of robust transit equity analyses. The data and methods presented here are based on publicly-available data in the US that, with minor modifications, could be used in other regions. These data are being continuously updated, making it possible to track accessibility in real-time, and are starting to see applications in the literature (see, e.g., 13). Previous academic work on accessibility has not translated well to practice. This work thus fills an important gap by tying advances in the academic literature to FTA-mandated analysis using publicly available data.

LITERATURE REVIEW

In the literature on transit ridership, two groups have been identified: choice and transit dependent riders (14, 15). Choice riders typically have an automobile available but choose transit for its high level of service for commute trips. 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 (14). This market segmentation creates important challenges for transit planners and for civil rights enforcement. A single transit agency responsible for a multimodal system has to make important choices regarding 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 on transit dependents and re-emphasis on choice riders due to the vagaries of US transportation policy and finance and other political-economic factors (15).

This shift in emphasis presents unique challenges for ensuring the civil rights of transit dependents are not violated and that, more generally, 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. Measuring discrimination is difficult. How it is operationalized can determine whether and the extent to which problems are identified (9, 16). In transportation analysis, accessibility has been identified as a fundamental metric of system performance (6).

Accordingly, accessibility – the ease with which destinations can be reached for a given transportation-land use configuration – has seen widespread application in both the literature and practice of transportation equity analysis (see, e.g., 17, 18).

Despite widespread application, operationalizations of transit accessibility in the literature have been inconsistent. 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 (19).

Typical studies of public transit in this tradition employ transit supply measures based on available data and transit demand measures from national censuses. Commonly employed measures of supply operationalize access as opposed to accessibility and include combinations of proximity to transit stops, frequency, availability, and network density (20-24). Other work has linked demographics to explicit indicators of place-based transit accessibility in the context of demographic needs (19, 25-28).

Each of the studies cited above was limited by its relatively coarse spatial scale and reliance on primitive representations of transit travel time almost exclusively based on regional travel demand model skims calculated at the transportation analysis zone (TAZ) level (but see 25). 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 (7, 13). More recent work has begun to incorporate 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 (13) or making national-level comparative assessments of transit service availability (29). This 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. Using these data sidesteps many of the limitations of prior sources and can result in metrics that more closely reflect the actual experiences of individuals that rely on public transit systems.

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. Some studies have examined project-level transit equity in terms of the distribution of travel time savings (30, 31). Others have calculated system-wide measures of transit service equity (32). Importantly, the literature has thus far engaged very little, if at all,
with federally-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.

**METHODS AND DATA**

Fundamentally, accessibility measures combine estimates of mobility (travel time, cost, or distance) with quantities of spatially dispersed opportunities (counts of jobs, shops, or services). For this paper, we employed data from OpenStreetMap, Valley Metro’s GTFS feed, and the US Census Longitudinal Employer-Household Dynamics (LEHD) dataset for the Phoenix metropolitan region. A key component of the methods involved software recently developed by the Environmental Systems Research Institute (ESRI) that allows GTFS data to be added to a traditional ArcGIS network dataset and included in standard network analyses. This innovation facilitates the calculation of highly disaggregate, temporally-specific transit travel times.

Calculating the accessibility metric employed here began with the creation of a 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. buffers using actual walking distances) around transit stops and stations. The standard FTA approach recommends Euclidian buffers of 1/4 mile around bus stations and 1/2 mile around rail stations. Using service areas instead of buffers will better represent the demographics and opportunities actually reachable within the specified distances.

Employed resident (worker) and job characteristics for each service area were subsequently aggregated using the LEHD for 2011. The LEHD provides block-level estimates of employed residents, jobs, and flows of employed residents to jobs for the United States. Census block centroids falling within each service area were included in the demographic calculations. The LEHD provides many job and worker categories, including wage-level, race/ethnicity, and job type. For this analysis we used worker and job locations for the three wage categories: low-wage (less than $1,250 per month), mid-wage ($1,251 - $3,333 per month), and high-wage (greater than $3,333 per month).

Travel times by public transit between service areas were calculated using standard ArcGIS network analysis approaches and the ESRI GTFS add-in. Trips were assumed to begin and end at the transit stop or station associated with the service area. To mitigate the effect of starting location and walking speed, the transit times assume all trips begin and end at the service area’s transit stop. Walking could occur along the street network if transfers were required, or at the end of a trip. A walking speed of 5 km/h was assumed, and trips that consisted entirely of walking were subsequently eliminated based on their speed. We estimated travel times for departures occurring during a two hour peak period (6:30 – 8:30 AM). A single estimate for each pair of stops was estimated by averaging the travel time assuming departures occurred randomly within nine 15 minute windows spanning the entire two hour period on a typical Monday. A cutoff of

---

1 https://mapzen.com/metro-extracts/
100 minutes of combined walk and transit travel time was used to make the computation tractable.

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

\[
A_{i}^{w} = \sum_{j} \frac{E_{j}^{w}}{n_{j}} e^{-\beta t_{ij}} \quad (1)
\]

\[
A_{i}^{w} = W_{i}^{w} \sum_{j} \frac{E_{j}^{w}}{n_{j}} e^{-\beta t_{ij}} \quad (2)
\]

where

- \( A_{i}^{w} \) = Accessibility at stop \( i \) for employed residents (workers) with wage level \( w \)
- \( W_{i}^{w} \) = Employed residents (workers) in service area at stop \( i \) of wage level \( w \)
- \( E_{j}^{w} \) = Jobs in service area at stop \( j \) with wage level \( w \)
- \( n_{j} \) = Number of transit stops contained in service area for stop \( j \)
- \( t_{ij} \) = Travel time (minutes) by transit between stop \( i \) and \( j \)
- \( \beta \) = empirically derived impedance term

\( i \) and \( j \) index the entire set of 7,445 transit stops in the Valley Metro system, and \( w \) indexes wage levels in the three LEHD income categories. Dividing the number of jobs in a service area by the number of total stops in that service area served to mitigate the effect of double counting. In addition to the accessibility values for each wage category, summing over all three provides an indication of the total, or overall, accessibility for a particular transit stop.

The impedance term was derived using ridership information from the 2010-2011 Valley Metro on-board survey (35). That dataset contained geocoded boarding and alighting locations. Travel times for each home-based work trip taken during the AM peak were determined using the GIS approaches described above, and the empirical trip-length frequency distribution was derived (Figure 1). In contrast to the lognormal distribution typically evidenced for automobile travel, the distribution of transit travel times is relatively more normal and indicating a much less rapid decay than found with automobile travel. Because of this revealed behavior, we set the impedance term to zero for jobs accessible within the mean travel time (54.2 minutes) and estimated it at 0.050 using nonlinear least squares for those jobs further than mean travel time. We subtracted the mean from travel times that exceeded the mean before use in equations 1 and 2. This approach to impedance is similar to assuming that transit users have a “built in” expectation of the length of a trip. Their propensity to travel by transit only decreases once this length is exceeded.
FIGURE 1 Trip length frequency distribution for walk plus public transit home-based work trips during the AM peak period.

The measure defined in equation 1 is similar to a cumulative opportunities accessibility measure in that it totals available opportunities from each origin, regardless of the characteristics of individuals at that origin. The measure defined in equation 2 explicitly includes the employed residents in the appropriate income category into the calculation. 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. Its employment (if any) will still contribute to the accessibility values calculated for other stops. The advantage of calculating accessibility in this way at the stop level is that it can be subsequently combined with appropriate queries of the GTFS database to combine accessibility information on all stops that belong to a route and to generate route-level measures that can be employed in transit service equity analyses.

RESULTS AND DISCUSSION

According to the LEHD, there were approximately 1.7 million total jobs and 1.65 million employed residents in the Phoenix-Mesa-Glendale Metropolitan Statistical Area (MSA) in 2011. The total number of employed residents and jobs in each wage category, along with those captured within a 1/4 mile walking distance of a bus stop or a 1/2 mile walking distance of a rail station are shown in Table 1. The table shows that about 48% of the region’s workers live within a reasonable walking distance of transit and that transit stops and that 75% of the region’s jobs are within walking distance of transit. It also shows that both low-wage and mid-wage resident workers are more likely to be located near to transit than high-wage resident workers. This finding is sensible, as high wage employed residents tend to be concentrated in the periphery of the region, far from where transit service is located. The spatial distributions of employed residents and jobs are shown for the three LEHD wage categories in Figure 2. Although the employed resident population appears to be spread widely throughout the metropolitan area, pockets of low-wage residents can be discerned in south and west Phoenix and south Glendale. Additionally, concentrations of high-wage employed residents appear in Scottsdale, north Glendale and some locations outside of the principal MSA cities. The distribution of jobs is more spatially concentrated, clustering along the major highway facilities in central Phoenix, Tempe,
and Mesa. The mix of jobs by wage level appears to be more uniform than the mix of resident worker location.

**TABLE 1 Valley Metro Service Coverage by LEHD Wage Level**

<table>
<thead>
<tr>
<th>Wage Level</th>
<th>Phoenix-Mesa-Glendale MSA total employed residents (workers)</th>
<th>Phoenix-Mesa-Glendale MSA total jobs</th>
<th>within pedestrian buffer of transit (percent of total) employed residents (workers)</th>
<th>within pedestrian buffer of transit (percent of total) jobs</th>
</tr>
</thead>
<tbody>
<tr>
<td>low-wage</td>
<td>384,314</td>
<td>399,034</td>
<td>192,700 (50%)</td>
<td>293,893 (74%)</td>
</tr>
<tr>
<td>mid-wage</td>
<td>620,384</td>
<td>646,730</td>
<td>325,117 (52%)</td>
<td>487,331 (75%)</td>
</tr>
<tr>
<td>high-wage</td>
<td>648,297</td>
<td>662,239</td>
<td>270,731 (42%)</td>
<td>498,134 (75%)</td>
</tr>
<tr>
<td>total</td>
<td>1,652,995</td>
<td>1,708,003</td>
<td>788,548 (48%)</td>
<td>1,279,358 (75%)</td>
</tr>
</tbody>
</table>

Sources: Valley Metro GTFS Feed, 2011 LEHD dataset.

Although Table 1’s aggregate, buffer-level analysis can provide a rapid diagnostic of transit service equity, simply having access to the public transportation system by proximity to a stop is a poor 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.

Figure 3 shows the results of calculating stop-level gravity measures of accessibility to all jobs. The left hand side of the figure shows the accessibility to jobs in all three wage categories for each transit stop in the network (equation 1). The results largely reflect the concentration of jobs within central Phoenix, Tempe, and Mesa. The result is not surprising; transit systems are built to connect areas of dense economic opportunities. However, by only considering the location of jobs, this accessibility metric misses a vitally important aspect of transit accessibility – the locations of workers that require access to those jobs. Because of the propensity of disadvantaged populations to spatially concentrate in US cities (see, e.g., refs. 36, 37), it is important to also employ resident location. The right hand side of Figure 3 addresses this limitation by weighting the overall measure by the number of workers within the service area of each stop (equation 2). The results show a much more differentiated pattern of accessibility throughout the region. A large swath of yellow (indicating very low accessibility) runs east-west south of downtown, and areas of high accessibility permeate outward into the urban fringe. By including the important element of transit demand into the accessibility formulation, equation 2 appears to provide a more nuanced and potentially more useful view of transit system functionality than equation 1.
FIGURE 2 Spatial distribution of (a) low-wage resident workers and (b) low-wage jobs in the Phoenix-Glendale-Mesa MSA. Principal cities in the MSA, major road facilities (Interstate and state highways). Each dot represents 125 resident workers or 250 jobs. Data from the 2011 Longitudinal Employer-Household Dynamics dataset.
FIGURE 3 Spatial distribution of stop-level gravity accessibility for two formulations: a) Total jobs accessible from each origin transit stop (equation 1) and b) Total jobs accessible from each origin transit stop weighted by the total number of residents in the service area around that stop (equation 2). Plotted categories of accessibility are grouped by quintile.
Spatial summaries of accessibility results like those shown in Figure 3 are difficult to interpret in the context of transit service equity and generally require further disaggregation or summarization to be made meaningful. Although groups of geographic units can be defined based on their demographic profiles (e.g. proportion of low-income residents in TAZs) and compared to one another, the definition of demographics is often arbitrary and not tied to clear policy directives or planning goals. Additionally, if cumulative measures are relied upon and combined with demographic profiles, it will often appear as though disadvantaged populations enjoy the highest accessibility by both automobile and transit because the areas of cities with the highest proportion of disadvantaged residents are often in close proximity to high concentrations of jobs.

One disaggregate summary unit that has not been previously analyzed in the literature but which is of obvious relevance to public transportation 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. Figure 4 shows the result of using equation 1 to calculate a gravity measure of accessibility for every transit stop in the network and aggregating the results to all 102 routes included in the Valley Metro system. Each panel in the figure shows one pair of wages: low-mid, low-high, and mid-high. Each route is plotted at a location simultaneously representing its average accessibility to jobs in both wage categories. Deviations from a straight line would indicate that some routes provide differing levels of accessibility by wage level. On the contrary, these results show that, in general, each route consistently provides accessibility to all three wage categories – as accessibility increases to jobs in one wage category they increase for the others. The light rail provides the greatest accessibility across all three wage categories.

There are differences in the absolute magnitude of accessibility provided to each group (as indicated by differences in scale on each axis); these are due simply to the differing number of total jobs in each of the LEHD’s three income categories (Table 1). If a particular route deviated substantially from providing equitable access across all three wage categories, it would be displaced from the linear trends evidenced in each panel of Figure 4. In the low range of Figure 4 b), there appear to be some deviations from equity, with some routes providing slightly greater accessibility to high-wage jobs than low-wage jobs, but existing conditions appear largely equitable. Because these results were based on equation 1, they only reflect the locations of jobs, not workers, and indicate that there is little economic segregation by wage category. Jobs of each type appear to be spread throughout the region.
Gravity measures of average accessibility to jobs for each transit route in the Valley Metro system for three pairwise comparisons by job type: a) low-wage and mid-wage, b) low-wage and high-wage, and c) mid-wage and high-wage. For each plotted point, average accessibility was determined as the mean of accessibility for all stops in a route as calculated using equation 1.

In order to provide a measure of accessibility linked to transit demand, Figure 5 uses equation 2 to compare the route-level accessibility for the two income categories expected to be most different – low-wage and high-wage. To account for differences in scale between the two measures, each point shown on Figure 5 represents the mean standardized accessibility for the route. To mute the large differences across different transit stops using this measure, we calculated a geometric mean by standardizing with the mean and standard deviation of the logarithm of all route-level accessibilities taking the exponential of the result. Because the results are standardized, outliers can be viewed by their deviation from the 1:1 line. Figure 5 illustrates again that most routes equitably provide accessibility to low-wage and high-wage groups. However, there are some notable outliers that only become visible when viewing the accessibility results in this manner. The Scottsdale neighborhood circulators and 12th Street local route provide greater accessibility for high-wage workers to high-wage jobs than they do for low-wage workers to low-wage jobs. In contrast to Figure 4, light rail appears to also provide a greater increment of accessibility to high-wage workers than low-wage workers, once the location of workers is taken into account. This is true even though, in both cases, light rail is the route that provides the greatest overall accessibility. It also provides an indication of the income of employed residents located within the light rail service areas. In the other direction, the Glendale urban shuttles provide relatively higher accessibility for low-wage workers to low-wage jobs than they do for high-wage workers to high-wage jobs.
This type of analysis is not capable of determining whether a particular configuration of transit service is equitable. It simply provides important information about the relative importance of different routes in a system that can be taken into consideration when undertaking transit system planning or proposing route changes. Because of the non-uniform distribution of people and jobs in regions, transit routes and modes that serve distinct populations are necessary to meet the often competing public goals of transit. One obvious area of application for this type of indicator, where normative considerations are pushed to the fore, is the FTA’s required transit service equity analysis.

**FIGURE 5** Comparison of standardized gravity accessibility for low-wage and high-wage jobs (calculated using equation 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.

**Application to FTA analysis**

By quantifying accessibility at the route level, the methods developed in this paper lend themselves well to federally-required service equity analysis (10). Presently, service equity analysis relies exclusively on comparing the demographics of routes slated to receive service changes to system-wide ridership (38). While important, demographic measures do not indicate how well particular routes connect populations to opportunities they would like to reach.

Figure 6 compares a typical metric used in FTA service equity analysis – proportion of boardings by low-income passengers – to the accessibility metric calculated using equation 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. This precisely matches the LEHD’s low-wage category (< $1,250 per month or $15,000 per year). Routes classified as low-income in Figure 6 therefore exceed 34% low-income riders. As can be seen from Figure 6, many routes that would not be considered low-income by the
transit agency are clearly of importance to low-wage travelers. In fact, 25 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 ridership proportions to determine the equity impacts of transit decisions: ridership proportions miss important information about the accessibility provided by and relative importance of different transit lines.

![Route-level transit ridership compared to route-level accessibility to low-wage jobs.](image)

FIGURE 6 Route-level transit ridership compared to route-level accessibility to low-wage jobs. The vertical line represents median accessibility. Points are jittered to reduce overlap.

The integration of an accessibility perspective into FTA analyses would be meant to supplement, not replace, the existing approach based on ridership. This is particularly important to emphasize, because routes with seemingly low accessibility could be providing vitally important lifeline connectivity to essential services like healthcare or education. The purpose of the present study was to demonstrate how emerging, publicly available datasets and readily-available software can be used to highly spatially resolved estimates of the accessibility of public transit systems. Using these estimates 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 ridership proportion does not push the route into the “low-income” category.

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 are expensive to operate and maintain, require specialized hardware, and take substantial time to complete a single run. Even when academic researchers have analyzed accessibility, they have had to rely on the provision of coarse skims derived from these regional models. 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 time period that spans several hours. The work presented in this paper has shown that publicly available data sources and commonly-available proprietary software can provide highly spatially and temporally resolved measures of public transit accessibility and information on transit equity relevant to compliance with FTA guidance.

Despite the technical advances developed in this paper, the methods contain some limitations that should be considered when interpreting the results. Although we were able to remove trips from consideration that consisted entirely of walking, we were unable to eliminate trips that mostly relied on walking. 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 buffer definition, depending on mode, to reflect the service area of 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, the work represents a substantial improvement over extant accessibility practice.

Increasing the spatial and temporal resolution of accessibility metrics improves the likelihood that the results will reflect the experiences of individual transit users and reduces the reliance on aggregate, zone-based measures.

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 and identify concomitant changes in accessibility. The results could be used to supplement and/or inform the expert opinions of transit planners or public participants. Another obvious extension would be to analyze 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. Non-work travel is therefore an important function of any public transit system.

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 tradeoffs and synergies inherent in both of these strategies is vital, but requires good data and tools. The results presented herein are presented as a modest step toward their development.

ACKNOWLEDGEMENTS
The author thanks Aaron Golub for helpful comments on the manuscript and Melinda Morang for timely technical support and updates on the GTFS/Network Dataset software.

REFERENCES


34. Morang, M. Z. Add GTFS to a Network Dataset. [http://www.transit.melindamorang.com/overview_AddGTFStoND.html](http://www.transit.melindamorang.com/overview_AddGTFStoND.html).


