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A comparative analysis of the challenges in measuring transit equity: definitions, interpretations, and limitations

Phillip R. Carleton*, J. David Porter

School of Mechanical, Industrial, and Manufacturing Engineering, Oregon State University, 204 Rogers Hall, Corvallis, OR 97331-6001, USA

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ABSTRACT

In the study of equity in public transit service distribution to disadvantaged groups, there is often a desire for a concise and relatable quantitative measure of equity. This ambition has often pushed researchers to develop methods for combining (or aggregating) various dimensions of disadvantage into a single, multi-faceted metric of potential transit demand (or need) among the disadvantaged population. These metrics then enable a somewhat straightforward analysis of the transit needs of the aggregate disadvantaged population to the transit service supplied in order to arrive at a measure of transit equity.

More recently, it has been proposed that such aggregated transit equity analysis may introduce veiled judgments or bias through the specific interpretation of key definitions and through the particular choices in the construction of a combined metric. It may also be the case that such an aggregate metric may mask or convolute important disparities in transit equity experienced by the various disadvantaged populations aggregated into a combined metric.

This research studies these issues through a clear discussion of the ambiguity and implied judgments often found in transit equity literature and then provides recommendations to mitigate these issues. Also, two common equity analysis methods are compared through a case study of public transit service in the city of Corvallis, Oregon, and a new transit service metric construction is introduced. By comparing the results of both the aggregated and disaggregated forms of disadvantaged group transit need within each analysis method, this study provides further evidence that important information may be concealed or easily misinterpreted when using aggregated descriptions of transit need.

1. Introduction

Public transit in the United States is a subsidized transportation service and, as such, it is considered a service required to be open and available to the entire public (Walker, 2012). It is this understanding of transit that drives one of its fundamental goals, i.e., to provide mobility benefits to the population as a whole. Unfortunately, this notion of responsibility to the public has occasionally been narrowly interpreted by transit providers and governments to mean only a bare minimum level of access to transit needs to be offered to everyone. However, the idea of public responsibility has come to mean transit service should instead be distributed based upon ideas of equity and need (Walker, 2008). Since the operation of public transit is inherently a spatial problem, equity in public transit service (from a regulatory standpoint) has historically had spatial considerations as integral, core components.

General transportation equity to disadvantaged groups has been made a progressively more explicit requirement through legislation and regulations such as Title VI of the 1964 Civil Rights Act, the 1994 Executive Order 12898, and the Transportation Equity Act for the 21st Century (TEA-21) (Marcantonio et al., 2017; Martens et al., 2012). These equity requirements have been carried over into recent legislation and guidelines, including the Fixing America's Surface Transportation (FAST) Act of 2015 and additional Federal Transit Administration (FTA) regulations, which require all federal funding recipients to distribute services equitably, mitigate disparate impacts, and conduct equity analysis if they service areas whose populations are larger than 200,000 (FTA, 2012a; 2012b). Often, these requirements are seen as too variable and vague because of the many definitions of equity used, the various analysis methods available, and the many possible subjective decisions and interpretations contained in the analysis methods (Karner, 2018; Karner and Golub, 2015; Marcantonio et al., 2017).

Therefore, the main goal of this research is to seek clarity in transit equity analysis by highlighting the many possible areas where degradations in clarity could be unwittingly introduced, and to offer

* Corresponding author.
E-mail address: carletop@oregonstate.edu (P.R. Carleton).

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mitigation suggestions. This is accomplished by 1) reviewing the manner in which quantitative methods are commonly applied for measuring and describing transit equity, 2) highlighting the qualitative issues that arise when using possibly ambiguous terminology (e.g., *equity, equality,* and *accessibility*), and 3) illuminating the assumptions inherent within a chosen methodological approach introduced through the transport disadvantage factors selected to include or exclude. It is also important to understand the benefits and limitations of two commonly used analytical methods in transit equity analysis, Lorenz curves with Gini coefficients and needs gaps, each coupled with the common practice of using aggregated depictions of disadvantaged group need. The hypothesis is that a lack of clear and explicit definitions, unacknowledged assumptions, biases, judgments, and aggregated measures of disadvantage group need, all combine to produce results which could be easily misinterpreted. These results could also obscure the unintentional (or intentional) judgements and values introduced by the methodological decisions (Brick, 2015; Walker, 2018). With support through literature, this hypothesis is explored by applying and comparing methods and their parameters in a case study.

The remainder of this manuscript is organized as follows. A review of relevant topics to this research study is presented, followed by a description of the methodology used for the case study. The results of the case study are discussed, and finally, the research findings, limitations, and opportunities for future work are presented in the conclusion.

2. Literature review

Transit-specific and equity-specific terminology can easily be misinterpreted as their common English usage lacks the specificity of meaning intended by researchers. This can lead to ambiguous statements or misinterpretation of results. In attempting to address any of the issues found in equity analysis, four key concerns arise from the literature:

- How is transit equity defined and understood (Garrett and Taylor, 1999; Kamruzzaman et al., 2016; Litman, 2016; Manaugh and El-Geneidy, 2012)?
- What are the set of factors chosen to represent some level of transport disadvantage (Al Mamun and Lownes, 2011b; Delbosc and Currie, 2011a; Fransen et al., 2015)?
- How are these definitions and factors then used to measure or quantify transit equity (Al Mamun and Lownes, 2011a; Grengs, 2015; Welch and Mishra, 2013)?
- What are the analysis methods used, and what are their accompanying assumptions and implications (Biba et al., 2010; Currie, 2010; Foda and Osman, 2010; Fransen et al., 2015)?

The following sections present the relevant prior work that was reviewed and synthesized to elucidate these questions.

2.1. Definition of equity

The term *equity* is often used interchangeably with the term *equality* which can lead to confusion. Therefore, it is critical to explicitly state the meanings of these two terms in transit research, and to acknowledge the possibility of ambiguity due to unclear use in prior literature. Generally, the concept of equality is understood to suggest that people or groups have the same rights and opportunities and should therefore be treated equally. It is helpful to think of equality as being related to “equal” or “sameness”. In the context of public transit, a goal of service equality would mean that all groups should be provided the same level of service. Therefore, equality is impractical and rarely the goal in practice or research.

In contrast, the concept of equity is understood to mean that, since people or groups may not have the same opportunities, they should be provisioned differently to address the disparities in opportunity (Brick, 2015). Thus, equity is more related to “fairness” or “justice”. With this definition of equity, inequity is then understood to refer to a lack of equity. In more recent transit equity analysis research, equity is further distinguished as either *horizontal equity* or *vertical equity* (Bandegani and Akbarzadeh, 2016; El-Geneidy et al., 2016; Pyrialakou et al., 2016; Welch, 2013). With these understandings of the terms, it is important to note that in transit equity research, it is the levels of equality which are measured directly. In order for a researcher to make claims of equity, subsequent analyses are required, or an explicit statement of the values and priorities used to relate equality to equity is needed. In other words, equality is not a subjective measure, but equity is always value based.

As opposed to horizontal equity (i.e., equity under the assumption of equally abled groups or individuals), the majority of transit equity literature focuses on the concept of vertical equity, which is concerned with situations where there is inequity experienced by disadvantaged individuals or groups. The latter are sometimes referred to as vulnerable groups, Environmental Justice (EJ) communities, or communities of concern (Rowangould et al., 2016; Welch, 2013). The drive is to then provide greater accessibility to these groups (e.g., minorities, poor, elderly, disabled, etc.) in order to achieve equity of opportunity.

Vertical equity is further divided with increasing specificity by Litman (2002), who uses “Vertical Equity with Regard to Income and Social Class” to refer to what generally may be understood as *socioeconomic equity*. The concept of socioeconomic equity is often the concern of those performing transit equity research. The terms social disadvantage, social exclusion, social justice, social sustainability, etc., as they relate to transportation, while distinct, are highly interrelated and are found addressing concerns similar to socioeconomic equity in the transit equity literature (Bennett and Shirgaokar, 2016; Dodson et al., 2004; Fransen et al., 2015; Kamruzzaman et al., 2016; Martens et al., 2012).

Litman (2002) uses the term “Vertical Equity with Respect to Need and Ability” to refer to the concept of *equity in mobility*. While factors of disadvantage often overlap, the concept of equity in mobility can be thought of as equity concerns for those who are disadvantaged by limited personal or transportation mobility (e.g., youth, seniors, spatially isolated, unlicensed, walkers, disabled, tourists, etc.). Most transit equity literature concerning equity in mobility is done in conjunction with analysis also containing factors of socioeconomic equity (Brick, 2015; Kaplan et al., 2014; Ricciardi et al., 2015).

2.2. Factors of transport disadvantage

When conducting research on vertical equity in transit, it is necessary to specify which set of factors will be used to define potentially disadvantaged groups. Since this set of factors then becomes the basis of the analysis into whether transit inequities exist between groups, their selection is considered one of the most critical steps in transit equity analysis (Foth et al., 2013). Within the transit equity literature, researchers often choose several factors to study. However, the factor of spatial location is always inherently included in transit research, predominantly through the relative location of domiciles to other locations of interest within a defined area.

The factors of disadvantage which can be broadly categorized as socioeconomic are those which stratify groups of people based on socially constructed concepts and delineations, as opposed to a physical or logistical disadvantage. The most commonly found socioeconomic factors in the transit equity literature are those that are also found across general social equity literature, and those mentioned in laws and regulations. They include race and ethnicity (Karner and Niemeier, 2013), income (El-Geneidy et al., 2016; Ricciardi et al., 2015), and employment status (Pyrialakou et al., 2016; Wixey et al., 2005). Less commonly seen factors include gender (Dobbs, 2005; Rogalsky, 2010), local language fluency (Litman, 2016), immigrant status (Bennett and Shirgaokar, 2016; Heisz and Schellenberg, 2004; Manaugh and El-Geneidy, 2012), and single parent status (Kramer and Goldstein, 2015;

Pyrialakou et al., 2016).

The ability and need factors are distinguished by a structural, logical, or physical constraint on mobility or access. Ability and need factors may overlap with socioeconomic factors, but their separate consideration is often needed for a thorough description of transportation disadvantage. For example, being low income or a recent immigrant may correlate with low vehicle ownership, but low vehicle ownership could also be associated with individuals of higher income levels due to lifestyle choices or to being more centrally located. Since ability and need factors may significantly constrain the transportation opportunities of an individual, irrespective of other socioeconomic factors, their inclusion in vertical equity studies is often warranted. The most commonly cited factors of ability and need are household car availability (Al Mamun and Lownes, 2011b; Jiao and Dillivan, 2013), age (e.g., youth, elderly) (Jiao and Dillivan, 2013; Wixey et al., 2005), and disability (Al Mamun and Lownes, 2011b; Hunter-Zaworski and Hron, 1999; Wixey et al., 2005). Less commonly seen ability and need factors include spatial and/or temporal isolation (Litman, 2016; Pyrialakou et al., 2016; Wixey et al., 2005), obligation level (e.g., trip frequency to school, work, medical care, etc.) (Litman, 2016; Wixey et al., 2005), and unlicensed/non-driver status (Case, 2011).

The factors of disadvantage ultimately chosen by researchers are determined with the objective of enabling a meaningful analysis, but their choices are often limited by data availability. For instance, Ricciardi et al. (2015) explored the factors of elderly, low-income, and zero car ownership based on the notion that individuals in these high-transit demand groups might suffer inequity through service distribution. However, the authors acknowledged that while several additional socioeconomic and need-based factors could affect levels of disadvantage, data scarcity on those factors prevented their inclusion in their study.

Al Mamun and Lownes (2011b) employed the same three factors as Ricciardi et al. (2015) plus forced car ownership and disabled individuals. The authors stated that these five factors were chosen because (1) these groups would have the greatest need for transit services, and (2) it was necessary to maintain consistency in units between the available data. The need for care in data processing and interpretation was also stressed in this study. More specifically, by only including employed individuals, it was acknowledged that the elderly and disabled groups were likely undercounted. On the other hand, methods were employed to avoid double counting in groups that were likely overlapping (e.g., low income and zero car ownership).

In other research studies, a larger number of factors are combined into somewhat complex indices to represent an overall level of disadvantage of an area. For example, Currie (2010) used a combined socioeconomic index consisting of over 30 individual components (e.g., % persons using internet at home, % females unemployed, etc.) and a needs-based index containing eight metrics (e.g., adults without cars, persons on a disability pension, etc.). Each of these two indices were then standardized and combined to create a single measure of transit need. While this method does allow for simplistic comparisons of transit supplies and needs, the simultaneous use of multiple levels of aggregation and multiple weighting schema introduce concerns about the interpretability of the results.

2.3. Measuring equity

As a precursor to understanding the measurement of equity, it is necessary to recognize and understand that there is a fair amount of variability in the definitions and methods for some key metrics measuring equity (Bennett and Shirgaokar, 2016; Manaugh and El-Geneidy, 2012). Key terms are often mistakenly used interchangeably, their meaning is not explicitly stated, or they may even vary in their precise meaning from author to author or within a document. The primary example of this issue is in the use of the terms *access* and *accessibility* which, when taken together, form a critical concept for measuring equity and for understanding transit analysis in general. Often the term access*,* together with accessibility*,* is defined generally for an individual (i.e., person-based) as how many useful or valuable things a person can do, or similarly, a person's ability to reach desired destinations, activities, goods, and services (Litman, 2003; Walker, 2012).

Viewed from a different perspective, accessibility is often intended to mean the level of convenience in accessing a given place, location, or activity (i.e., place-based or “reachability”) (Hansen, 1959). To complicate matters, accessibility is sometimes implied to refer only to a narrower subject domain. For example, in transit-specific research it can be used to mean the ease and convenience with which people can reach transit services (Al Mamun and Lownes, 2011b), or the ease and convenience with which people can access various locations via a transit network (sometimes referred to as “connectivity”) (Kaplan et al., 2014). Still, other authors use accessibility to mean multiple definitions. Xu et al. (2015) employed this multi-use definition, and the meanings are distinguished by appending the terms “to transit” and “by transit” to accessibility. The former distinction (i.e., “to transit”) has been logically split into origin-access and destination-access, which consider distances from a transit stop to a final destination in addition to origin-to-stop distances (Murray, 2001). The authors use the “by transit” definition to refer to a person-based measure of access enabled by the service, and it is dependent on issues such as network connectivity, travel times, and fares.

The lack of a universally employed definition of accessibility was noted over a decade ago (Schoon et al., 1999), but the distinction between person-based versus place-based and space-based versus space-time-based accessibility is still an active topic (Kaza, 2015; van Wee, 2016). Exemplifying the ease of confusion when using these terms is the fact that an increase in the access “to transit” increases accessibility “by transit”, thereby increasing both the overall access and mobility of an individual and the measure of accessibility of locations within the service area of transit systems. The communication and consistency of how accessibility (and thus equity) is defined and measured is a critical component for clear interpretations of transit equity analysis results. Transit researchers need to both acknowledge the current and historical issues surrounding the definition of access and accessibility and clearly establish their intended meanings.

Once an understanding of accessibility is established, it can be used as a basis to gauge the equity in transit service distribution. A common approach in quantifying equity is to perform gap analysis. In this method of defining equity, researchers highlight disparities between the services provided to and the services needed by a group or location (Currie, 2010; Fransen et al., 2015). Another common approach is to use Lorenz curves and Gini coefficients to show the deviation from complete equality (although described as equity in literature) in the cumulative distribution of service to various disadvantaged groups (Cheng et al., 2015; Delbosc and Currie, 2011b; Kaplan et al., 2014; Ricciardi et al., 2015; Welch and Mishra, 2013). Using these two main comparative methods (i.e., gap analysis and Lorenz curves), many different types of equity analysis are possible through the myriad alternative constructions of measures of accessibility and the numerous ways to characterize disadvantaged groups.

2.3.1. Gap analysis

The studies using the gap analysis method generally follow the concept of illuminating a mismatch between transit supply and the mobility needs of those it is intending to serve (i.e., an inequitable distribution of service). Gap analysis in transit is most often referred to as “needs gap” analysis, a term first used in transit research by Currie (2004), but with aspects being included in a rural accessibility study in the UK as early as the late 1970s (Moseley, 1979). While the definition and construction of metrics of supply (most commonly accessibility) and needs (i.e., potential demand) have varied greatly over time and among researchers, the basis in the method of comparing these two metrics has remained somewhat consistent. Through varying the components and the construction method of these supply and needs metrics, researchers have been able to study a diverse set of issues in transit equity (Pucher, 1982; Rogalsky, 2010; Truelove, 1993; Tribby and Zandbergen, 2012; Wang et al., 2014).

As previously discussed, one of the critical issues in analyzing transit equity is in the definition and construction of a measure of accessibility (i.e., transit supply). Generally, a spatial depiction of the calculated needs gap metric for geographical zones is developed to visualize its distribution. Fransen et al. (2015) found that the lowest decile of need gap was generally situated in more urbanized areas and covered a relatively small proportion of the study area. Conversely, the highest decile of needs gap was generally in lower density areas and covered a much larger proportion of the overall area. This was an expected result as travel time was the major component of transit supply, but aside from one analysis of elderly access to physicians, the results conflate all disadvantaged groups into a single aggregate metric. A valid interpretation of these results seems problematic in that the equity experienced by the constituent disadvantaged groups cannot be separated, i.e., it could be that some groups experience greater inequity than others, but this information is lost in the aggregation. Also, it should be understood that the gap method is attempting to compare disparate measures with each other through transformations to a common scale. This can make the interpretation of the results somewhat challenging. However, even in light of these issues, the relative comparisons of study area need gaps can still be of value with clear, disaggregated measures of transit need.

2.3.2. Analysis based on Lorenz curves and Gini coefficients

Similar to the gap analysis method, analyzing transit equity with Lorenz curves and Gini coefficients is based on a measure of transit supply. However, rather than directly comparing accessibility to a spatially defined measure of disadvantage or need, the cumulative proportion of a transit supply is mapped to the cumulative proportion of the disadvantaged population metric, thereby creating a Lorenz curve. The Gini coefficients are then calculated as the proportion of the area between the Lorenz curve and the line of equity (area A in Fig. 1) and the total area under the line of equity (the sum of areas A and B in Fig. 1). Using this approach to construct the Gini coefficients, the values will fall between 0 (representing total equity) and 1 (representing total

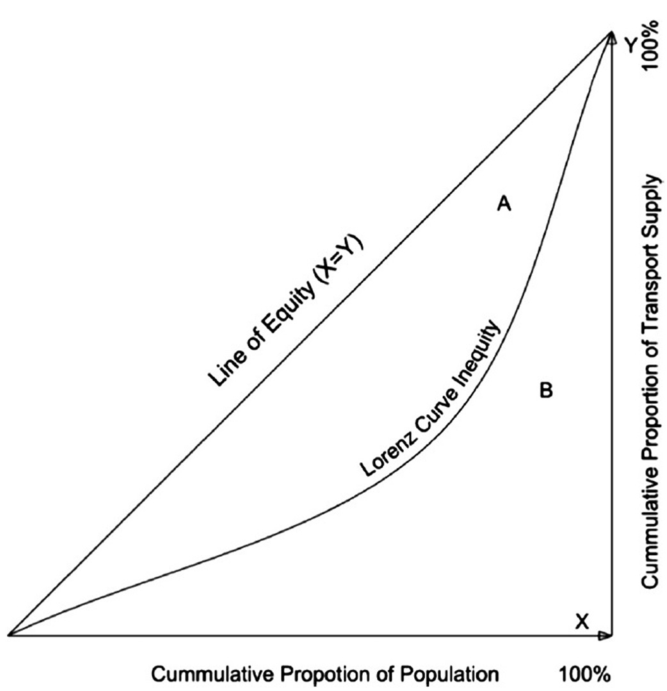

Fig. 1. A Lorenz curve and line of equity Source: Ricciardi et al. (2015).

inequity). The traditional use of the term equity in this method (e.g., Line of Equity) is more appropriately understood as a measure of equality since it is the relative distribution among a population.

One advantage of using Lorenz curves is that information on service to various percentiles of the population in question can be further analyzed. For example, by studying the cumulative distribution shown by a Lorenz curve, Ricciardi et al. (2015) found that in Perth, Australia, 70% of the total population was delivered only 33% of the entire transit supply. A limitation of the Lorenz curve method is that the results are spatially disassociated, and additional analysis is required to understand the spatial implications (Ricciardi et al., 2015). However, the prime advantage of using the Lorenz curve and Gini coefficient method is that an overall measure of transit equality experienced by a group is produced for the entire study area, as opposed to the spatially dependent results obtained through gap analysis. This allows easy comparisons of the transit access experienced by various populations within a study area, or between separate study areas, for the purposes of benchmarking and more nuanced understanding of service distributions to disadvantaged groups. The disparities seen in transit access through Lorenz curve analysis can then serve as a basis for defining whether or not those disparities in equality of access represent an equitable situation (Welch and Mishra, 2013).

2.4. Aggregation in equity analysis

Even though there are many guidelines and regulations in determining particular disadvantaged groups (e.g., EJ communities/populations/areas (i.e., low-income and/or minority) for EO 12898 compliance (FTA, 2012b; Holifield, 2012; Rowangould et al., 2016), and Title VI protected groups (i.e., minority and immigrant) (FTA, 2012a; Karner, 2018)), it has been found that these guidelines and requirements can fall short of a thorough description of the transit equity landscape as experienced by a comprehensive and diverse set of disadvantaged populations (Karner, 2018). It has also been noted that often these aggregate definitions can mask, convolute, or misrepresent levels of inequity among various disadvantaged populations (Brick, 2015; Delbosc and Currie, 2011a; Jacques et al., 2013), but this critique is often overlooked as seen in the practice of constructing a simple, aggregate measure of disadvantage (El-Geneidy et al., 2016; Fransen et al., 2015; Manaugh and El-Geneidy, 2012). This shortcoming is even sometimes noted, but still used in the interest of simplicity (Currie, 2010).

It is the argument of this paper that the opposite tends to come to fruition. That is, the goal of simplicity through the use of a single, combined measure of disadvantage or need actually complicates the results rather than simplifying them. It is then the aim of this research to study this assertion and to provide examples and recommendations for clearer uses of common methods.

3. Data and methods

Data from many sources were compiled and processed to create the required metrics and to enable the comparison of the methodologies for analyzing transit equity. The population and demographic information were sourced from the Census Transportation Planning Products (CTPP) dataset from the American Association of State Highway and Transportation Officials (AASHTO). The CTPP dataset was chosen as it consists of special tabulations of the 5-year American Communities Survey (ACS) datasets specifically for the purposes of transportation planning and analysis (AASHTO, 2017). This data source also conveniently provided the demographic estimates already in special geographic delineations known as Transportation Analysis Zones (TAZs). The datasets for count estimates in each TAZ for Total Population, Poverty Status, Minority Status, Age (for both Youth and Elderly), Linguistic Isolation (i.e., Limited English Proficiency (LEP)), and Zero-Vehicle Households (ZVH) were obtained as shapefiles from CTPP's

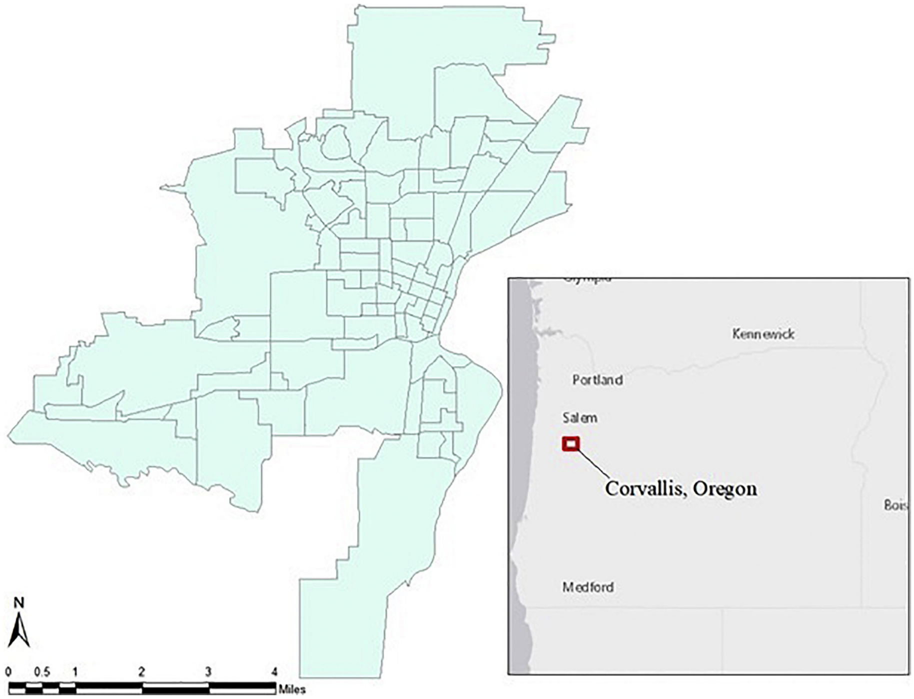

Fig. 2. TAZs in case study area of Corvallis, OR.

most recently published tabulations (2006–2010, 5-year estimate data). Finally, transit supply data were sourced from OpenStreetMap (OSM) road network data and a General Transit Feed Specification (GTFS) dataset of transit service.

The geographic area serviced by the Corvallis Transit System (CTS), which includes the cities of Corvallis and Philomath, Oregon, was selected as the case study area for this research and is shown in Fig. 2.

A set of 86 TAZs (illustrated in Fig. 3a) which overlap the CTS service area were chosen to serve as the basis for analysis. The OSM road data, CTPP data, and GTFS data were all combined and processed in ArcGIS 10.5 to create the complete dataset for the 86 TAZs in the case study area. For the purposes of this study, only TAZs that intersected a quarter-mile walk-access buffer around a CTS bus stop (illustrated in Fig. 3b) were considered for investigation.

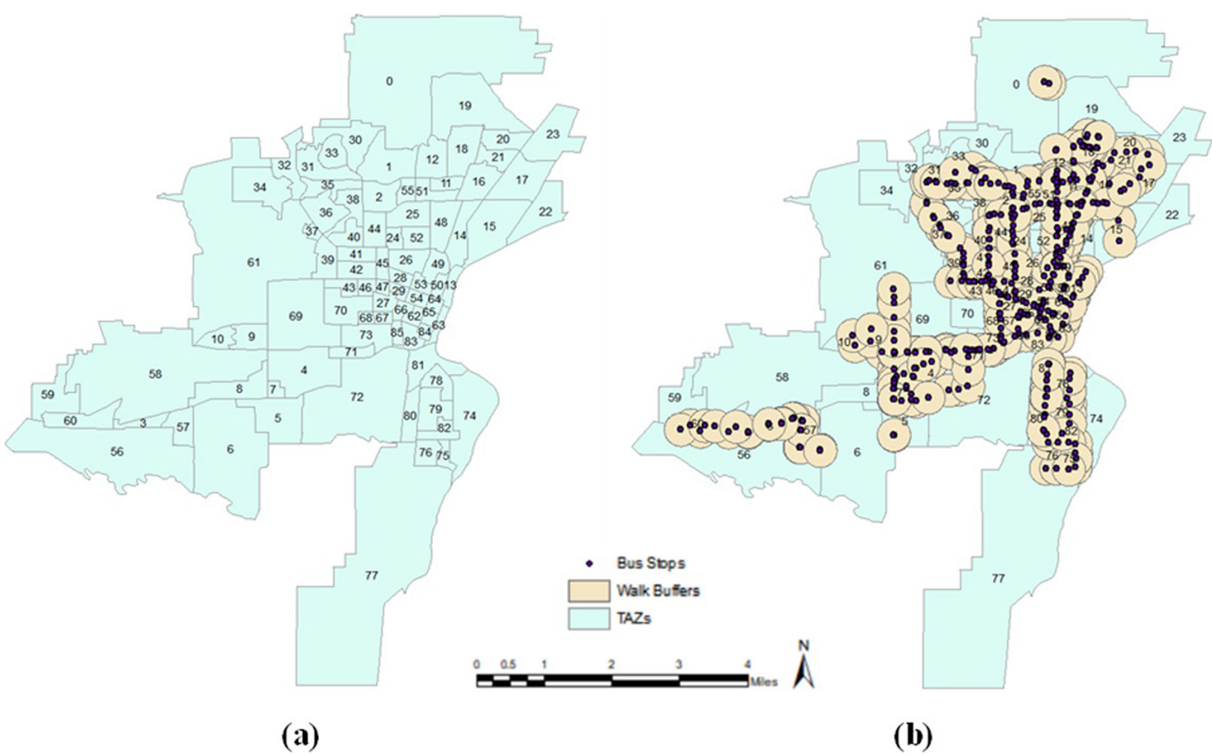

Fig. 3. (a) 86 TAZs in case study area, and (b) CTS stops and walk access buffers.

3.1. Disadvantage metrics

Several factors were chosen to represent populations which could be considered disadvantaged. These factors were selected based on their inclusion in prior research (Grengs, 2015; Jaramillo et al., 2012; Kahrobaei, 2015; Kramer and Goldstein, 2015) and on data availability. While LEP is acknowledged as a factor potentially causing transportation disadvantage (Litman, 2016), it was not found to have been previously selected as a factor in transit equity analysis literature and is included here as an additional contribution to the field. Through this selection process, it is important to note the implied judgments made in choosing disadvantage factors to include or exclude. For example, disabled populations are often considered to be a transportation disadvantaged group (Hunter-Zaworski and Hron, 1999; Litman, 2016). However, supplementary paratransit services (including demand-response transit) are often supplied by public transit providers to these populations and, therefore, the levels of equity for these groups may not be properly defined using the same methods as those for fixed-route transit analyses.

For each of the 86 TAZs in the case study area, the CTPP datasets were used to construct one disaggregate disadvantage metric for each of the groups listed in Table 1; one aggregated disadvantage metric using equal weighting for all groups in Table 1; and a metric for the total population. “Elderly” was defined as the population estimated between 65 and 74 years old plus the population estimated as > 75 years old. “Poverty” was created as a combination of the groups “Households < 100%” and “Households between 101% - 149%” of the federal poverty level.

For the disadvantage metrics, the count estimate data was first converted to a proportion (relative to the population within each respective disadvantaged group) for each TAZ. A scaled version of each metric was also created to be in the range from 0 (the minimum value) to 100 (the maximum value). For the aggregate disadvantage metric, the individual, disaggregate metrics were combined with equal weighting to avoid making any explicit judgments about the relative importance of these factors of disadvantage as in Brick (2015). The scaled versions of the metrics were utilized in the needs gap method to allow direct comparison to the supply metric, whereas the proportional versions of the metrics were utilized for constructing the Lorenz curve and Gini coefficients.

3.2. Supply metrics

To construct a measure of the level of transit service supplied to a TAZ, a method similar to that in Delbosc and Currie (2011a, 2011b) was used. The supply metric was calculated as:

$$SM_{TAZ_j} = \sum_{i=1}^{n} \left(\frac{RL_{B_i}}{RL_{TAZ_j}} \times SF_{B_i} \right) \tag{1}$$

where:

SM_{TAZ_j} = Supply metric for TAZ_j, for $j = 1, 2, \ldots, 86$
n = Number of quarter-mile walk access buffers for bus stops in TAZ_j
RL_{TAZ_j} = Total road length in TAZ_j
RL_{B_i} = Road length covered by buffer i within bounds of TAZ_j
SF_{B_i} = Service frequency to buffer i (as measured by average number of bus arrivals per week)

Table 1
Groups for which demand/needs metrics were constructed in each of the 86 TAZs.

Group	Description
Youth	Count of persons < 16 years old
Elderly	Count of persons > 64 years old
LEP	Count of linguistically isolated persons > 5 years old
Minority	Count of non-white persons
Poverty	Count of households with incomes < 150% of federal poverty level
ZVH	Count of households with zero vehicles

While conceptually similar to the method in Delbosc and Currie (2011a, 2011b), the decision in this research study to use a weighting based on the proportion of road length covered represents a more realistic construction of a supply metric enabled through new GIS analysis tools (Biba et al., 2010; Foda and Osman, 2010). This decision was intended to better address the commonly applied assumption of uniform spatial distribution of populations within TAZs. It has been acknowledged that this assumption can lead to misrepresented service levels, especially in rural (i.e., less densely populated) areas (Bertolaccini and Lownes, 2013; Currie, 2010; Ricciardi et al., 2015), and that this network-ratio method helps reduce overestimation of populations served (Biba et al., 2010). However, it should be noted that the supply metric construction employed in this research implicitly makes the assumption that populations are uniformly distributed along a road network. This method may also not fully describe the population distribution. However, it is generally the case that large, rural TAZs also have more sparse road networks around which populations cluster; and this “proportion of road length covered” weighting method seeks to incorporate this phenomenon when representing transit service coverage.

3.3. Lorenz curve and Gini coefficients analysis

The Lorenz curves and Gini coefficients for the eight analyses (i.e., total population; six disaggregate disadvantage metrics; and one aggregate disadvantage metric) were constructed following a common procedure (Delbosc and Currie, 2011a, 2011b; Ricciardi et al., 2015). The Lorenz curves were each constructed by mapping the ordered, cumulative proportional supply metric to the cumulative proportional disadvantage metric. The Gini coefficients were then approximated using the following equation:

$$G = \frac{A_{LC}}{A_{TIE}} = 1 - \sum_{k=1}^{n} (X_k - X_{k-1})(Y_k + Y_{k-1}) \tag{2}$$

where:

G = Gini coefficient
k = TAZ index, $k = 1, 2, \ldots, n$ ($n = 86$)
A_{LC} = Area between the equity line and the Lorenz curve
A_{TIE} = Total area under the equity line
X_k = Cumulative proportion of the disadvantage metric; $X_0 = 0$, $X_1 = 1$
Y_k = Cumulative proportion of the ordered transit supply metric; $Y_0 = 0$, $Y_1 = 1$

It is important to note that because of the choices made in constructing the supply and disadvantage metrics, this analysis is only comparing the proportional distribution of the existing service to the proportion of the various disadvantaged populations. As such, this is a *relative* measure of the equality in the spatial distribution of transit service and it intends no judgments as to the appropriateness or fairness of current service levels to the various groups. The analysis merely intends to uncover the discrepancies in the distribution of transit services to the groups. It should also be understood that, while the Lorenz curve method does not present spatially linked outputs, there are spatial delineations used to define the inputs, which impart spatial implications (e.g., locations of residences, bus stops, etc.) to an interpretation of the method's results.

3.4. Needs gap analysis

The needs gap method utilized the same eight measures of transit need and one of transit supply. These values were then mapped to their respective TAZs, as depicted in Fig. 4, where darker colors represent

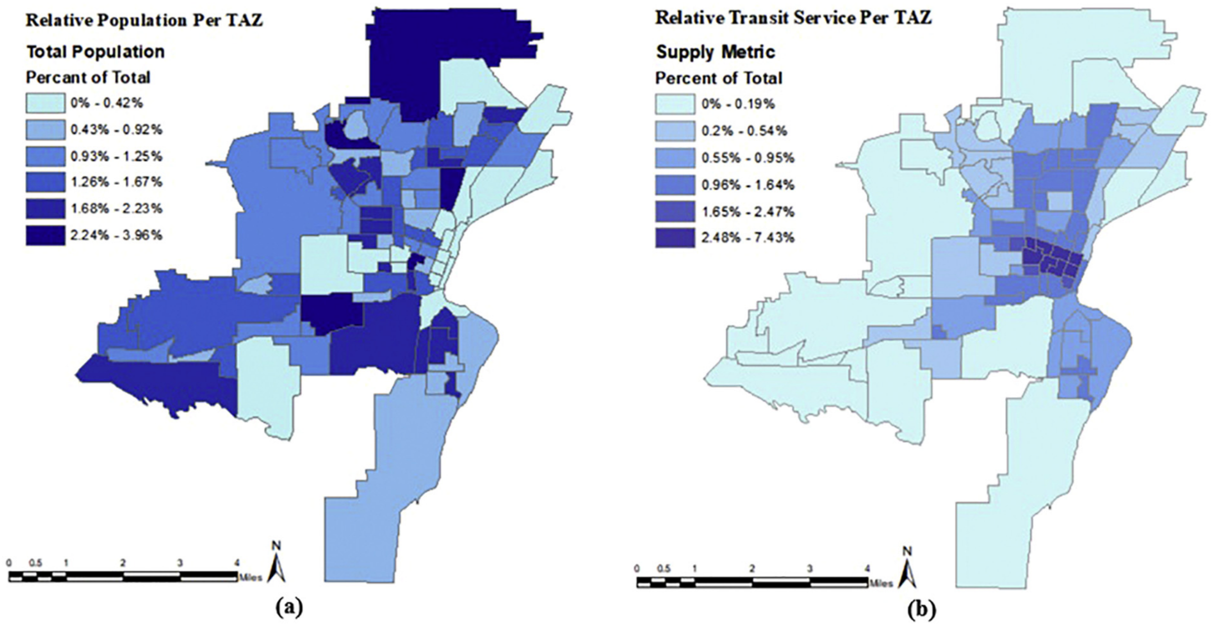

Fig. 4. (a) Total population based transit need and (b) Supply metric spatial distributions.

increasing values of the metric. However, the method of construction of these measures differed in that the rescaled versions of the metrics were used instead of the proportional versions. This, in essence, preserved the relative ordering and magnitude of the values while transforming them to all be on the same scale, allowing for the direct comparison of supply and need measures. Also, like the Lorenz curve method, the aggregate disadvantage metric used equal weighting for each of its constituent elements. The needs gap of the total study area was then calculated by summing the absolute values of the final needs gap metric for each TAZ. A new measure called *total needs gap* (TNG) was created to allow for comparison of relative transit equality between the eight analyses, with larger numbers representing greater inequality.

4. Results and discussion

4.1. Lorenz curve method

As part of the analysis based on the Lorenz curve method, the equality of transit distribution to the overall population was calculated for the CTS service area to serve as a basis for comparison. The Lorenz curves for "Total Population" and "Combined Factors" are shown in Fig. 5, along with their corresponding Gini coefficients (i.e., G = 0.53 and G = 0.55). Here it can be seen that the aggregate metric of

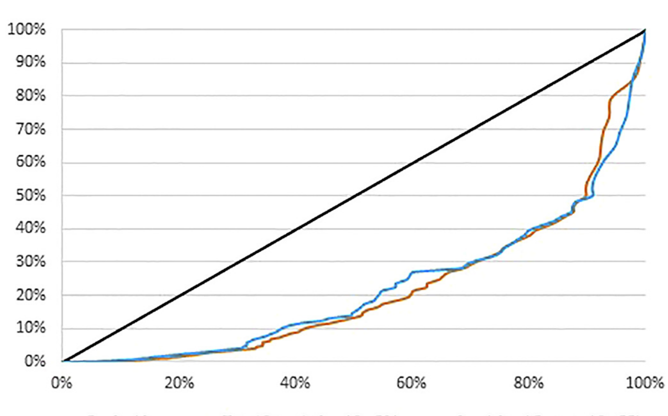

Fig. 5. Total population vs. aggregate disadvantaged Lorenz curves.

disadvantage tracks relatively closely with the general population. These results suggest that while there is inequality evident in the distribution of transit service, it is not markedly different for the disadvantaged population as compared to the overall population and, therefore, it could be argued that no special considerations for these groups are necessary.

The results of the Lorenz curve equity analysis to disaggregated disadvantaged groups depicted in Fig. 6 seem to show a different picture. As evidenced in Fig. 6, the equality of transit service to a particular group can vary significantly. Compared to the total population, the results indicate that youth (Fig. 6a) and elderly (Fig. 6b) experience much greater inequality; poverty (Fig. 6e) and ZVH (Fig. 6f) experience much less inequality; and LEP (Fig. 6c) and minority (Fig. 6d) experience about the same level of inequality. Contrary to the results of the aggregate analysis presented in Fig. 5, these analyses may indicate that certain disadvantaged groups warrant consideration in inequity mitigation efforts.

One advantage of the Lorenz curve method is shown in the ease with which a relatable magnitude of inequality may be expressed. For example, it can be seen in Fig. 6a that around 75% of the youth in the study area share only about 20% of the transit service provided; in contrast, about 60% of the total population shares 20% of transit service. Another insightful way of interpreting the Lorenz curves is illustrated by Fig. 6f, which shows that the TAZs receiving the combined lowest 50% of the transit service, contain about 80% of the ZVHs. Coupled with the Gini coefficients, the Lorenz curve method also allows for easy comparisons of equality between groups. For example, the Gini coefficients easily reveal the consequential finding that there is significant divergence in equality for aggregate and disaggregate definitions of disadvantage groups.

4.2. Needs gap method

The results of the analysis based on the needs gap method depicted in Fig. 7 appear somewhat different than those obtained through the Lorenz curve method when comparing relative levels of inequality experienced by the overall population. For example, the results depicted in Fig. 7a indicate there is much greater inequality in transit service distribution to the overall population than to a combined disadvantaged group (Fig. 7b). This can be seen though the spatial

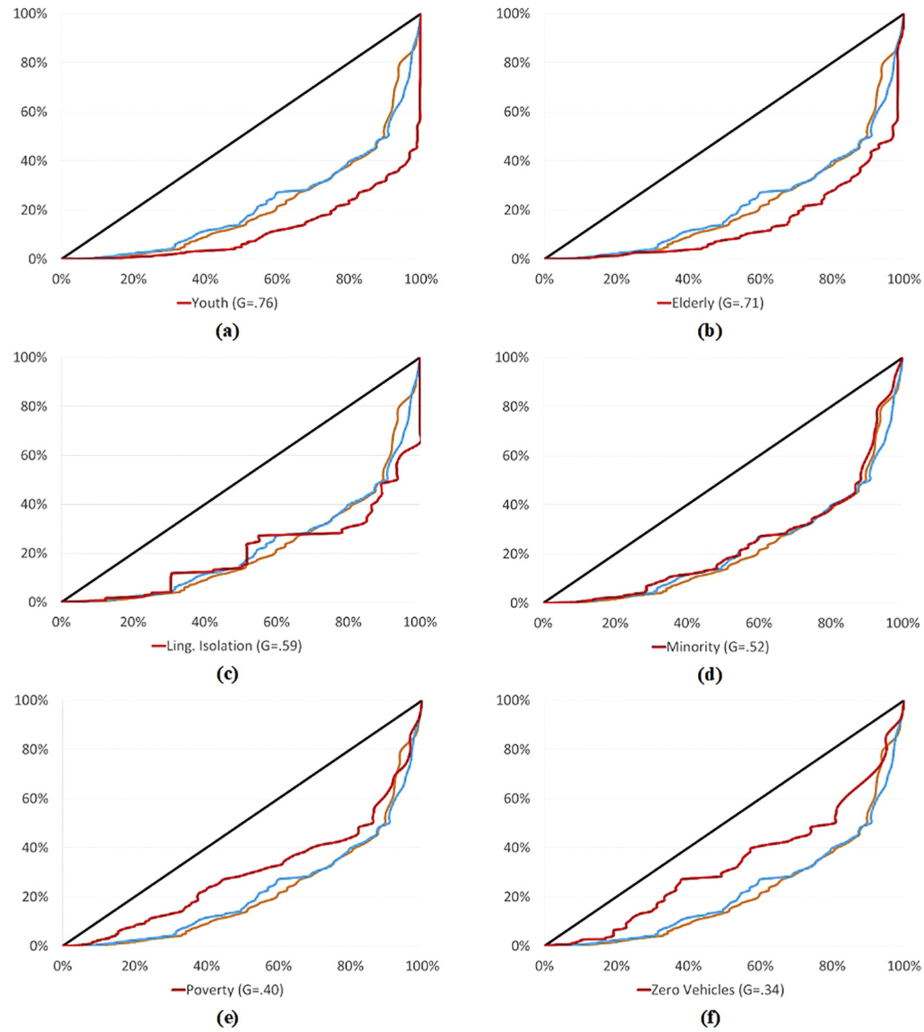

Fig. 6. Disaggregate disadvantaged group Lorenz curves.

depiction in which underserved TAZs are shown in red and orange, and overserved TAZs are shown in dark and light green. Also, the TNG value for the total population (2166.84) is larger than the TNG value obtained for the combined factors (1437.13). It would therefore be a reasonable argument that the transit service is already improving vertical equity since it benefits disadvantaged groups to a larger degree than the overall population. In contrast, the results of the analysis based on the Lorenz curve method depicted in Fig. 5 showed these two groups to be much more comparable, which would seem to preclude such an argument.

The results of the disaggregate disadvantaged group needs gap analysis can be seen in Fig. 8. These results are more generally in line with the ordinality of the disaggregate analyses of the Lorenz curve method, with the notable exception of the “Poverty” and “LEP” analyses switching positions. With the needs gap method, only the group of “Youth” is seen to experience greater inequality than the overall population, whereas with the Lorenz curve method, three disaggregate disadvantaged groups and the aggregate disadvantaged group were all found to experience greater inequality than the overall population. Most significant is that, similarly to the Lorenz curve method, several disaggregate disadvantaged group analyses reveal either greater or lesser inequality than is exhibited in the aggregate disadvantaged analysis.

The spatial depiction of inequality enabled through the use of the needs gap method has some important advantages. First, it may reveal patterns to researchers over regions larger than the TAZ-based geography area as seen in the Corvallis downtown area (i.e., small green TAZs in Fig. 8) and Philomath area (i.e., western most TAZs in Fig. 8). Second, it allows analysts to distinguish between under- and over-served areas within a particular disadvantaged group and areas consistently under- or over-served across several disadvantaged groups. For instance, the Corvallis downtown area is often seen as overserved whereas outer regions are most often underserved. There is also a trapezoidal shaped TAZ north of the Corvallis downtown area (seen colored red in Fig. 8c-f) consistently underserved. This type of information is quickly noticed and easily interpreted with the needs gap method, but these patterns would be less apparent through the Lorenz curve method. The uncovering of these patterns may help target specific mitigation efforts.

4.3. Comparison of Lorenz curve and needs gap methods

Through the analysis of transit equality in the case study, it can be seen that each of the two most commonly used analysis methods have their unique advantages and drawbacks. While the Lorenz curve method is good for simple, cross-analysis comparisons and relatable equality interpretations in terms of proportions of a total, it does not allow for easy spatial comparisons or interpretations of equality within an analysis area. Conversely, the needs gap method excels at providing easily assimilated and understood spatial equality patterns within an analysis, including the distinction of under- and over-served areas. However, it does not allow for easy comparison of overall equality

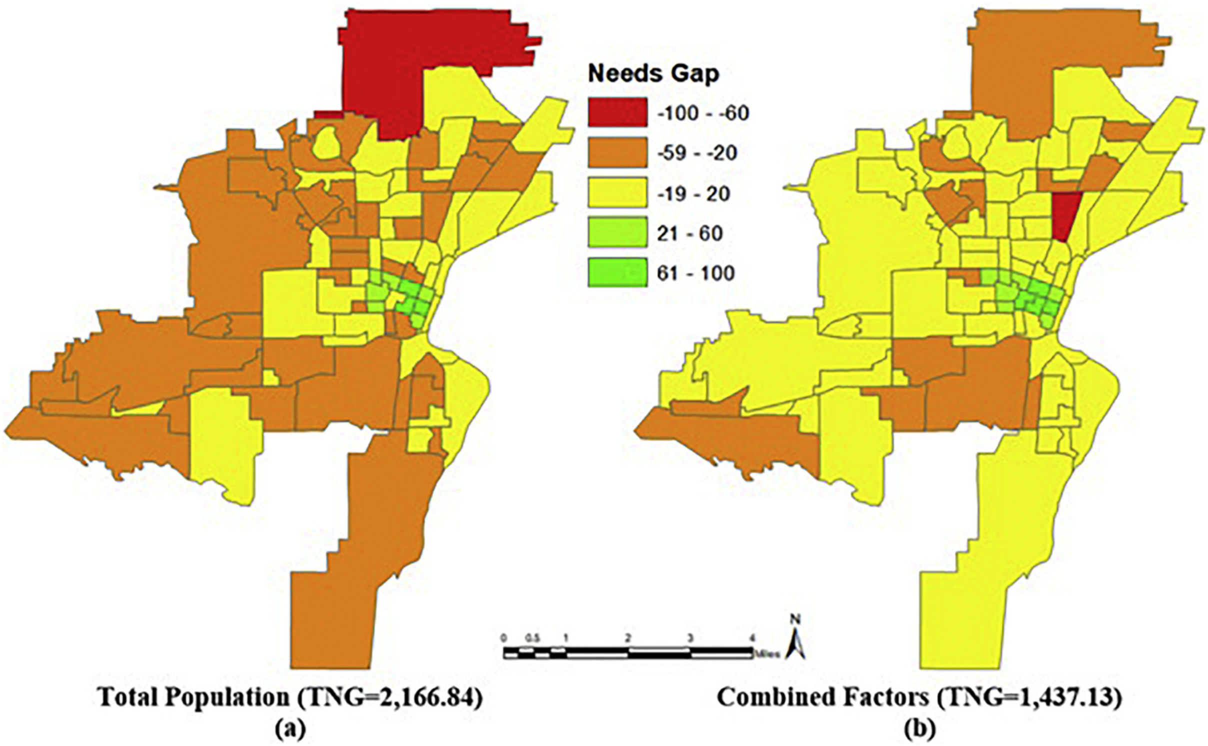

Fig. 7. Total population vs. aggregate disadvantaged needs gaps.

across analyses (in this case, across disadvantaged groups), and it requires the transit need and service data to be rescaled to a common level for direct comparison. The TNG metric is a feature introduced by this research effort as an expansion to the needs gap method in order to provide some level of cross-analysis comparison similar to the Gini coefficient of the Lorenz curve method. The equal treatment of underserved and overserved areas, however, may be problematic for ease of interpretation and use, and is the likely cause of the slight divergence in results between the two methods. For these reasons, it is possible that researchers will find the simultaneous use of both methods to be a preferred practice for producing the fullest description of transit equality. For analysts with more specific goals, a single method may prove the most effective way to analyze equality due to a method's inherent strengths.

An important finding of this research, and one in which both methods are consistent, is that the aggregated metrics of disadvantage produced descriptions of equality often in conflict with those using disaggregate measures of disadvantage, possibly masking divergent levels of equality experienced by disadvantaged groups. For instance, the large level of inequality in the “Elderly” and “Youth” disadvantaged groups appeared to be significantly lowered and the smaller level of inequality in the “ZVH” disadvantaged group appears to be increased in the combined disadvantaged metric analysis for both methods. It is likely that these larger and smaller levels of inequality cancel each other out in a combined metric analysis, and also likely that various weighting schemes could produce markedly different results. It should be understood that the obfuscation and implied judgments inherent in creating such an aggregated metric may preclude both the holistic interpretation and the applicable utility of the analyses which use them.

5. Conclusion

This paper explores the nuanced and intricately defined topic of equity in the spatial distribution of transit service to disadvantaged populations and contributes to the field by highlighting common challenges and possible pitfalls when conducting such analyses. These issues include the need to clearly and explicitly state the intended definitions of key terms, the practice of acknowledging the possible subjective bias and judgments introduced when making methodological decisions, and the need to exercise care in interpreting results.

This paper also contributes by illuminating the advantages and limitations of using two common equity analysis methodologies. In their most commonly applied forms, Lorenz curve analysis is recommended if overall equality comparisons between groups or study areas is the goal and needs gap analysis was shown to be most effective when spatial patterns of equality within a study area are of primary concern. However, the results indicate the fullest and most detailed description of transit equality seems to be possible with the combined use of the two methods. Most importantly, through the case study of transit service in Corvallis, OR, this research provides further evidence that the common practice of creating aggregate measures of disadvantage can fall short in producing meaningful measures of transit equality. Researchers and analysts would be well served to have ample justification and thorough interpretations if choosing to aggregate disadvantaged populations.

5.1. Limitations

It is important to understand the limitations of this study, especially when attempting to interpret the results as a representation of the real-world experience of disadvantaged populations. For instance, this study shows that the “Elderly” and “Youth” populations experience the greatest inequality across methods. While this may be accurate with respect to the location-based access to the fixed route transit service, these results may not be indicative of the overall, person-based transportation accessibility experienced. Individuals in the “Youth” group are not able to operate a personal vehicle, but they may have access to other means of transportation (e.g., school bus, a driving guardian, family carpools, etc.). Likewise, “Elderly” populations often have additional transportation options (e.g., dial-a-bus, senior center shuttles, etc.). For an accurate understanding of the public transportation equity of such groups, it is likely necessary to investigate the specifics of each

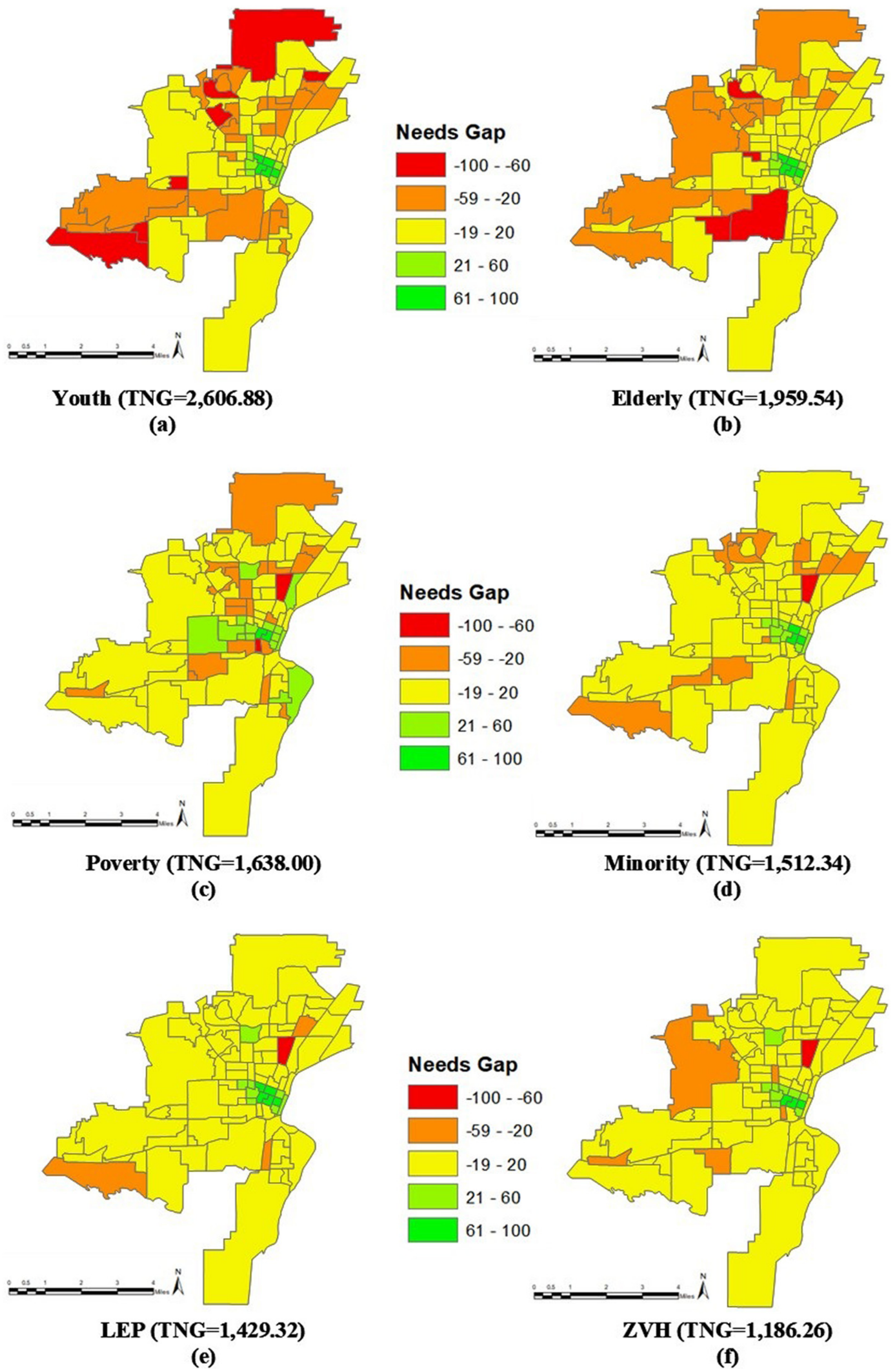

Fig. 8. Disaggregate disadvantaged group needs gaps.

scenario in greater detail.

Another key point in any attempt to directly interpret the results illustrated in the analyses of this study is to understand the inherent judgement in the selection and construction of the metrics used. As discussed, the categories of disadvantaged populations selected for inclusion (and those excluded) unavoidably create implied and, too often, undiscussed judgements. Similarly, any weighting scheme chosen in creating an aggregate measure of disadvantage also carries with it the same types of implied judgments. Another primary limitation relates to the previous discussion of the confusion existing in terms equity and equality. With the working definitions employed in this research, what has been attempted to be measured and compared is equality. However, it is often necessary to refer to it as "equity analysis" since that is the commonly used term in the literature. It is difficult to reiterate the point sufficiently that the equality measured is only a starting point for a determination of equity. The leap to equity necessitates the introduction of individual priorities and values since it is based on the subjective notion of fairness, and it is this leap which has been explicitly avoided in this research.

5.2. Opportunities for future work

The findings from this research offer many opportunities for further study in the area of transit equity. In addition to addressing the limitations discussed, the adoption of clear and robust methods for quantitatively describing transit equality may enable new opportunities for targeted mitigation and equity optimization efforts. For instance, with reliable and meaningful quantitative measures of equality, operational decisions (e.g., fare structures, route shapes, vehicle headways, etc.) may be optimized to maximize equity under given resource constraints. Heuristic and metaheuristic optimization models are likely to be adept at handling such complex systems and may be able to progress the research beyond merely describing existing levels of equality to actively planning future services around maximizing transit equity.

This research combined with ongoing efforts to produce more accurate and complete ridership datasets also enable future transit equity study (Porter et al., 2017). For example, with accurate, spatially and temporally disaggregated (i.e., hourly, stop-level) ridership data, the estimated demographic data currently used as a proxy for potential demand becomes less important. Data collected by buses and trains equipped with new automated passenger counting and automated fare collection technologies, coupled with recently developed ridership data standards open the possibility for highly specified datasets (e.g., rider socioeconomic and personal mobility characteristics, origin-destination pairs, temporal factors and effects, etc.). This data availability coupled with the concepts in this research may also open the possibility for more detailed analyses and finely targeted mitigation strategies.

Such availability of a more granular dataset of spatial population distributions and demand patterns would open opportunities to improve the allocation of populations to the stops which service them. As previously mentioned, the assumption that populations are equally distributed along the lengths of roads in a road network within a TAZ may not hold in some cases. Also, as the accuracy of an equality measure was not the focus of this research, a simple weighted bus stop frequency was used as a description of the level of transit service, but it is possible to create much more detailed and inclusive service metrics. Future work could expand the service metric introduced in this research to include elements such as spatial and temporal connectivity, time and monetary costs and benefits, rider safety and security, and connecting pedestrian networks and amenities.

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Declarations of interest

None

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