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Advances and pitfalls in measuring transportation equity

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Abstract
Transportation systems play a pivotal role in facilitating access to out-of-home activities, enabling participation in various aspects of social life. But because of budgetary and physical limitations, they cannot provide equal access everywhere; inevitably, some locations will be better served than others. This realization gives rise to two fundamental concerns in transportation equity research and practice: (1) accessibility inequality and (2) accessibility poverty. Accessibility inequalities may rise to the level of injustice when some socioeconomic groups systematically have lower access to opportunities than others. Accessibility poverty occurs when people are unable to meet their daily needs and live a dignified and fulfilling life because of a lack of access to essential services and opportunities. In this paper, we review two of the most widely used approaches for evaluating transport justice concerns related to accessibility inequality and accessibility poverty: Gini coefficients/Lorenz curves and needs-gap/transit desert approaches, respectively. We discuss how their theoretical underpinnings are inconsistent with egalitarian and sufficientarian perspectives in transport justice and show how the underlying assumptions of these methods and their applications found in the transportation equity literature embody many previously unacknowledged limitations that severely limit their utility. We substantiate these concerns by analysing the equity impacts of Covid-19-related service cuts undertaken in Washington, D.C. during 2020. The paper also discusses how alternative methods for measuring transportation equity both better comport with the known impacts of such changes and are consistent with underlying moral concerns.

Keywords Accessibility · Justice · Egalitarianism · Sufficientarianism · Transport poverty · Transport inequality

Introduction

Transportation plans and projects distribute benefits and burdens across people and places; the transportation equity literature provides methods that can be used to determine whether these distributions are fair and just (Karner et al. 2016; Martens et al. 2012; Pereira and Karner 2021; van Wee 2011). The origins of transportation equity research and practice lie

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in the disproportionate burdens that low-income people, specific racialized populations,[1] and other marginalized groups have faced—and continue to face—because of their exposure to the negative externalities of transportation infrastructure including noise, pollution, and crash risk, among others (Feitelson 2002; Forkenbrock and Schweitzer 1999; Schweitzer and Valenzuela 2004), and the disparate benefits they receive from transportation planning efforts in terms of proximity to transportation services and access to opportunities (Lucas and Jones 2012; Rosenbloom and Altshuler 1977).

Despite substantial research quantifying transportation benefit and burden distributions (Pereira et al. 2017; Schweitzer and Valenzuela 2004; Vecchio et al. 2020), there is still a lack of clarity about the limitations of the methods used in the literature and little discussion about how they are underpinned by different moral concerns. Relatedly, there is scant work examining whether the metrics and measures we calculate and apply meaningfully reflect the real-world conditions that people face. In other words, we know little about whether our approaches meet the standard of face validity. The question of *how* we should best measure and assess transportation equity so that our results comport with lived experiences is rarely asked explicitly, with notable exceptions (e.g., Carleton and Porter 2018; Humberto 2023; Lucas et al. 2019; van Wee and Mouter 2021).

Two methods have been widely used in the literature to operationalize two fundamental transportation equity concerns: transport inequality and transport poverty (Carleton and Porter 2018; Lucas et al. 2019; van Wee and Mouter 2021). The Lorenz curve and Gini coefficient have been extensively used to measure and visualize transport inequalities, examining how transport benefits/burdens are distributed among and between people and places (e.g. Delbosc and Currie 2011; Lucas et al. 2016b; Pritchard et al. 2019b). In contrast, needs-gap and transit deserts approaches have been widely used to operationalize transport poverty using an apparent "gap" between public transit supply and demand (e.g., Delbosc and Currie 2011; Jiao and Dillivan 2013). Studies in this tradition seek to understand the extent to which individuals and groups have access to an acceptable level of transportation services and resources to enable barrier-free participation in daily life activities.

In this paper, we present a literature review that critically engages with the use of Gini coefficient/Lorenz curve methods and needs-gap/transit desert approaches to measure and examine transportation equity. We demonstrate the limitations of these methods by analyzing public transit accessibility changes in Washington, D.C. implemented at the beginning of the Covid-19 pandemic in early 2020. Accessibility describes the ease with which destinations can be reached as shaped by available transportation modes, infrastructure, levels of service, and affordability, as well as land uses, socioeconomic characteristics, and temporal factors (Geurs and van Wee 2004). While the arguments and methods presented in this paper can be used to evaluate transport inequalities and poverty more broadly, our analysis focuses on accessibility issues because accessibility describes the foundational benefit that transportation systems provide (e.g., Cui and Levinson 2020;

[1] We deliberately use the terms racialization and racialized populations to highlight that groups are only understood to constitute a race through various processes and deliberate actions. Using alternative terms such as racial or ethnic minority obscures the process of racialization, implies that race and ethnicity are immutable characteristics that refer to relevant biological differences, and denotes a lesser status. Referring instead to "specific racialized populations" highlights that race categories are social constructions while calling attention to the processes of exclusion and discrimination that dominant groups use to maintain power. For further discussion, see Hochman (2019) and Hochman (2021).

Handy 2020; Levine et al. 2019; Martens 2012).[2] Our work advances the literature in three ways, by:

1. elucidating how moral political philosophy's egalitarianism and sufficientarianism can inform transport inequality and poverty measurement;
2. revealing conflicts between moral principles and Lorenz/Gini and needs-gap/transit desert approaches; and.
3. proposing alternative methods to advance transportation research and planning aligned with moral goals.

The paper is organized as follows. The sections "Accessibility inequality" and "Accessibility poverty" delve into those areas of research and practice, discussing their moral and philosophical foundations, measurement approaches, limitations, and alternative methods. The subsequent sections, "Data and methods" and "Study area," provide details about our procedures and an overview of Washington, DC demographics and public transit conditions, respectively. We use the Washington case to validate and substantiate our arguments. In the "Results and discussion" we apply both standard and alternative methods to evaluate Covid-19-related transit service cuts. The work demonstrates that prevailing equity analysis methods can easily mislead analysts, decision makers, and the public. We close with thoughts about how the field can move forward with these insights in mind.

Accessibility inequality

Decisions regarding the allocation of limited capital investments and operating expenditures necessarily result in uneven service and accessibility conditions across neighbourhoods and demographic groups. This realization raises fundamental concerns about accessibility inequalities, particularly as low-income people and specific racialized populations, among other marginalized groups, are the ones who have historically been left behind (Bullard et al. 2004; Bullard and Johnson, 1997; Grengs 2005).

A growing number of studies have focused on quantifying inequalities in access to opportunities (Delbosc and Currie 2011; Farber et al. 2014; Giannotti et al. 2021), and on assessing how the accessibility benefits of transport investments accrue more to certain population groups than others (Golub and Martens 2014; Grengs 2015; Karner 2018; Pereira 2019). Questions of accessibility inequalities are fundamentally motivated by egalitarian concerns, even though these concerns are rarely articulated explicitly (Lucas et al. 2016b; Pereira and Karner 2021).

[2] Lucas et al. (2016a) make a distinction between transport poverty and accessibility poverty, identifying the latter as a "sub-concept" of the former. They additionally identify mobility poverty, transport affordability, and exposure to transport externalities as components of transport poverty. Upon closer investigation, these three additional components all relate to accessibility in the sense that greater mobility and affordability are associated with greater access. Reduced exposure to externalities also facilities access by enhancing safety and physical health, for example. Still, some analysts may prefer to evaluate mobility, affordability, or exposure to externalities without reference to accessibility. Accordingly, we use accessibility inequality and poverty when referring to our analysis and transport inequality and poverty when speaking more broadly about potential applications and insights.

Egalitarian concerns

Egalitarianism is a strand in moral political philosophy undergirded by the notion that all individuals have equal moral worth and thus should be treated as equals in some respect, even though different theories disagree about the relevant currency of equality (Arneson 2013; Sen 1979). Accordingly, egalitarian perspectives are concerned with the distribution of goods and bads among people and they seek equality along some societal dimensions (Kymlicka 2002). These dimensions typically encompass equality of opportunity rather than equality of outcomes (Kymlicka 2002). Particularly for Rawlsian and luck egalitarians, individuals should not be disadvantaged due to morally arbitrary circumstances beyond their control, such as being born with a physical disability, into a low-wealth family, into a specific racialized group or gender, or in a particular country (Rawls 2001; Roemer and Trannoy 2016). Policies and practices that seek to mitigate these circumstances by equalizing opportunities are consistent with egalitarianism. Importantly, egalitarians recognize that equalizing opportunities may still entail different treatment. An egalitarian state can result when people experience different levels of goods and bads, but all experience similar levels of dignity, worth, and equal access to opportunities. Lorenz curves and Gini coefficients are often used in the literature to operationalize egalitarianism in the context of transportation equity evaluations because they fundamentally measure how equal (i.e., even) a given distribution is (Delbosc and Currie 2011; Lucas et al. 2016b; van Wee and Mouter 2021).

The Lorenz curve and Gini coefficient

The Lorenz curve was originally proposed as a graphical representation of the distribution of income in a population (Salverda et al., 2011). It plots the accumulated distribution of income along the y-axis versus the accumulated distribution of the population ranked by income level (from the poorest to the wealthiest) along the x-axis. The resultant line connecting each of the cumulative shares is the Lorenz curve (Fig. 1). The Gini coefficient is calculated as the ratio of the area between the Lorenz curve and the line of equality (45 degrees) to the total area under the line of equality. The Gini coefficient ranges from 0 to 1, with 0 indicating complete equality (i.e., everyone has the same amount) and 1 indicating complete inequality (i.e., all values are concentrated in one person).

Gini coefficients and Lorenz curves in the transportation equity literature

Since the early 2000s, the Lorenz curve and Gini coefficient have seen increasing use among researchers studying and quantifying various forms of transportation inequalities, including household transport expenditures (Berri et al. 2014), CO_2 emissions (Luo et al. 2016), number of daily trips (Shirmohammadli et al. 2016), traffic fatality risks (Abdalla 2002; Elvik 2009), and transit connectivity and service levels (Bertolaccini and Lownes 2013; Kaplan et al. 2014; Song et al. 2018). In these cases, the Lorenz curve is constructed by plotting the accumulated distribution of a transport-related good

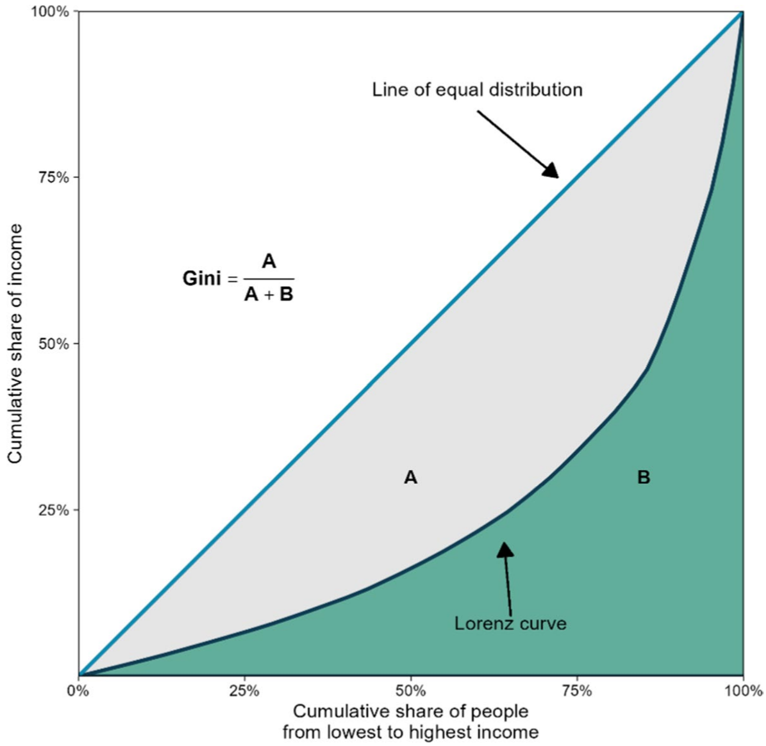

Fig. 1 The Lorenz curve and Gini coefficient

or bad (e.g., accessibility or transport cost) on the y-axis, and the accumulated distribution of the population ranked by that transport variable on the x-axis.

The Lorenz curve and Gini coefficient have also been used to examine accessibility inequalities, either in terms of access/proximity to transit stops (Delbosc and Currie 2011; Jang et al. 2017) or access to opportunities including jobs (Ben-Elia and Benenson 2019; Tomasiello et al. 2020; Zhu and Shi 2022), government services (Neutens et al. 2010), schools (Guzman et al. 2017; Sharma and Patil 2022; Talen 2001), retail stores (Tahmasbi et al. 2019), and medical facilities (Park et al. 2023; Rong et al. 2020).

Gini/Lorenz and their limitations

Studies of accessibility inequalities interpret Lorenz curve and Gini coefficient results to understand whether a transportation system or policy is equitable. However, when closely examined, such applications face multiple limitations that render them incompatible with egalitarian concerns. We identify five major issues that severely limit these methods:

1. **Emphasis is on equality, not equity.** The normative outcome implied when a Gini coefficient is used is perfect equality—a coefficient of zero. And lower values are always preferred to higher ones. However, an egalitarian distribution is not necessarily perfectly equal across all individuals. Indeed, different people and groups require different levels of multimodal accessibility to achieve the egalitarian standard of equal opportunity.

Prioritizing transit services in socially vulnerable and transit-dependent communities would be consistent with egalitarianism even though it might entail increasing overall inequality.

2. **Vertical equity is not captured**. The differentiation between groups required by egalitarianism is appropriately captured using a normative "vertical" equity perspective but is completely absent in the "horizonal" equity perspective often employed in Lorenz/Gini applications (e.g., Chen et al. 2019; Giuffrida et al. 2023; Tahmasbi et al. 2019). Horizontal equity is often defined as a claim for equal treatment of people considered equal in ability or need (Litman 2017). Equality within groups is the relevant yardstick in that case, but defining both "ability" and "need" is nontrivial in transportation applications (e.g., Boisjoly and El-Geneidy 2021). As a result, studies often claim to estimate horizontal equity by calculating a Gini coefficient over an entire city or region without controlling for differences in abilities, needs, or socioeconomic conditions (e.g., Allen and Farber 2019; Delbosc and Currie 2011). Moreover, because horizontal equity requires similar individuals to experience similar conditions, horizontally equitable conditions would result if, for example, low-income groups had equally low access to opportunities, even if higher income-groups had disproportionately higher accessibility.
3. **Comparisons are unordered**. Lorenz curves and Gini coefficients do not account for socioeconomic conditions when measuring transport-related inequalities. When used to measure transport inequalities, the Lorenz curve ranks individuals by the level of their transport variable (e.g., accessibility) irrespective of their socioeconomic characteristics. This means that the Lorenz curve and Gini yield inequality estimates that are fundamentally unordered by socioeconomic status, which creates additional problems.
4. **Direction of inequality is ambiguous**. These approaches cannot distinguish between conditions in which accessibility inequalities are concentrated among the most-disadvantaged or least-disadvantaged groups. This limitation also renders Lorenz curves and Gini coefficients incapable of determining whether a given policy is progressive or regressive. In a hypothetical case, accessibility inequality measured with Lorenz/Gini would drop equally if a policy intervention improved the accessibility of wealthy neighbourhoods with low access or reduced the accessibility of low-income neighbourhoods with relatively high accessibility. But neither of these alternatives would be considered equitable.
5. **Only within-group (rather than between-group) inequalities are reported.** Lorenz curves and Gini coefficients capture the total inequality within a population or group, but they are silent regarding the inequality between disadvantaged and better-off groups. Despite this limitation, researchers have interpreted comparisons between Gini coefficients calculated separately for different groups or different places as providing estimates of inequalities between groups (e.g., Azmoodeh et al. 2021; Wang and Lindsey 2017; Welch 2013). This is not correct; Gini coefficients provide no information about which group experiences better or worse overall conditions.

Alternative approaches for measuring accessibility inequality

Accessibility inequalities can be measured with alternative methods that overcome the limitations of Lorenz curves and Gini coefficients, but these alternatives have been much less adopted in the literature. Three of these methods, along with their strengths and weaknesses, are discussed below: the Theil index, Palma ratio, and concentration index.

Theil index

Whereas the Gini coefficient quantifies the degree of inequality within a group, the Theil index explicitly quantifies inequality both within and between groups (e.g., for mutually exclusive spatial regions or sociodemographic categories) (Conceicao and Ferreira 2000). The Theil index is decomposable into these two quantities and the overall Theil is simply the sum of the between- and within-group inequalities. In the transport context, the Theil index has been used to examine the distribution of bikeability (Hamidi et al. 2019), inequalities in access to healthcare (Jin et al. 2022), and public libraries (Delafontaine et al. 2011), as well as the equity impacts of cordon pricing (Souche et al. 2016) and transport network optimization (Santos et al. 2008).

Because the Theil index can be decomposed, it can be used to build counterfactual scenarios that simulate how total inequality would change if all inequalities between groups were eliminated while keeping the inequality within groups and vice versa. The Theil index also has some limitations. Its maximum value depends on the population size, making communication and comparisons difficult. Because the calculations involve logarithmic transformations, the measure does not consider individuals experiencing values of zero. Perhaps the most important limitation of the Theil index from a transportation equity perspective is that it does not perform an ordered comparison of individuals or groups ranked by their socioeconomic position. It thus shares many of the limitations inherent in the Lorenz curve and Gini coefficient.

Palma ratio

The Palma ratio is an inequality measure that captures both inequality between groups and considers their rank ordering. Cobham and Sumner (2013) originally proposed the Palma ratio to measure income inequality, drawing inspiration from the work of Palma (2011), who showed that the share of income earned by those in the middle 40–90% of earners was remarkably stable across countries and time. Accordingly, the Palma is calculated as the ratio of the total income of the top 10% of earners to total income of the bottom 40%. The measure focuses attention on the two parts of the income distribution most likely to shift and corrects for the Gini coefficient's known insensitivity to changes at the upper and lower ends of the distribution.

In transport studies that focus on accessibility inequalities by income, the Palma ratio is often measured as the ratio of average accessibility for the wealthiest 10% to average accessibility for the poorest 40%. It has been used to measure accessibility inequalities in different contexts including Colombia (Guzman and Oviedo 2018), Brazil (Herszenhut et al. 2022), the United States (Liu et al. 2022), the United Kingdom (Banister 2018), and the Netherlands (Pritchard et al. 2019a).

The Palma ratio is easy to communicate. It also provides an ordered comparison between disadvantaged and better-off groups. Nonetheless, it ignores middle-income categories. Another limitation of the Palma ratio is that, because it only compares averages, it overlooks inequalities within groups. This same limitation applies to studies that measure inequalities using ratios between groups such as Black and white travelers (Pereira et al. 2021), individuals with and without a physical disability (Grisé et al. 2019), and other mutually exclusive categories along age, sex, transport mode, or other dimensions (Allen and Farber 2019).

Concentration index

One promising but underused alternative approach for measuring transport inequalities is the concentration index (CI). The CI was originally developed to measure tax progressivity (Kakwani 1977; Suits 1977). Like the Gini coefficient, the CI is calculated with reference to a concentration curve. Like the Lorenz curve, the CI's concentration curve also shows the cumulative distribution of accessibility on the y-axis. The difference is that with the CI, the population along the x-axis is ordered by a socioeconomic variable that is measured on an ordinal or continuous scale (such as income or education) and not by individual accessibility levels. As such, CI measures the extent to which inequalities in a given variable are systematically associated with socioeconomic status.

In its original formulation, the CI is defined as twice the area between the concentration curve and the line of equality, the 45-degree line. The CI can theoretically vary between − 1 and + 1 when all accessibility is concentrated in the most or in the least disadvantaged person, respectively. Negative values indicate that inequalities favour disadvantaged populations, while positive values indicate better conditions for the well-off. As such, one advantage of CI is that the sign and the magnitude of the index indicate, respectively, the direction and the strength of the relationship between accessibility and socioeconomic position.

Although the CI has been widely used to analyze inequalities in health (Clarke et al. 2002; e.g., Kakwani et al. 1997), it has received little attention in the transport literature. Two exceptions are Chen et al. (2013), who used the CI to examine socioeconomic inequality in crash-related disabilities, and Rubensson et al. (2020), who analysed the socioeconomic inequality of accessibility and the progressivity of a skip-stop train policy introduced in Stockholm, Sweden.

Some limitations of the CI have been documented in the literature and enhanced versions of the index have been proposed to address them (Clarke et al. 2002; Wagstaff 2005). Erreygers (2009) proposed a "corrected concentration index" (CCI) that overcomes these shortcomings and satisfies the "transfer property." In a transportation equity context, this property requires that an inequality metric should capture a reduction in inequality when there is an increase in accessibility for a disadvantaged person or a reduction in accessibility for a well-off person, and it should indicate an increase in inequality if the changes go in the opposite direction. Erreygers's CCI also normalizes accessibility by the lower and upper bounds of the distribution, instead of by the average, easing comparisons. The CCI can be calculated using Eqs. 1 and 2,

$$w_i = r_i - \left[\frac{(n+1)}{2}\right] \tag{1}$$

$$CCI(a) = \frac{8}{n^2(m_x - n_x)} \sum_{i=1}^{n} a_i w_i \tag{2}$$

where n is the population size, a_i is the accessibility of individual i, w_i is the weight attributed to the accessibility of individual i, r_i is the socioeconomic rank position of individual i, beginning with 1 for the worst-off individual, and m_x and n_x are the upper and lower bounds of the accessibility variable, respectively.

Accessibility poverty

Accessibility poverty is a state in which a person's ability to access essential activities, including work, school, health care, and leisure becomes so low that they are unable to satisfy basic needs (Allen and Farber 2020; Lucas 2012, 2004). Accessibility poverty can result from different causes, including lack of an automobile (Klein et al. 2020), poor public transit service (Zhang et al. 2022), unaffordability (Perrotta 2017), physically inaccessible vehicles and spaces (Levine and Karner 2023), and sociocultural environments that are hostile to women, queer people, specific racialized populations, and others (Lubitow et al. 2017). Addressing accessibility poverty requires removing transportation barriers and/or enhancing service so that people can meet their basic needs. Concerns about minimal levels of acceptable benefits or maximum levels of acceptable burdens are the province of sufficientarianism (Lucas et al. 2016b; Pereira and Karner 2021).

Sufficientarian concerns

A sufficientarian perspective of justice is primarily concerned with understanding the extent to which everyone experiences acceptable levels of benefits and burdens given what is considered a minimum standard of living in a society (Kymlicka 2002). Sufficientarians are particularly concerned with absolute levels rather than relative distributions (Arneson 2013). Injustices emerge not because of inequalities between groups, but rather because some are faced with conditions that undermine their ability to live a minimally decent and dignified life. Studies that adopt a sufficientarian approach to transportation equity commonly share a core belief that there is a minimum level of transport resources, services, safety, or accessibility necessary for people to fulfil basic needs with dignity, or conversely that there is a maximum acceptable amount of transport externalities, such as air pollution or fatality risks, that would hinder them from doing the same (Pereira and Karner 2021).

A key challenge for transport poverty studies involves articulating the baseline level of transport-related goods/bads against which the conditions of individuals should be assessed. Ideally this level would not be solely based on the existing population distribution, rather it would flow from political deliberations undertaken by affected populations and be supported by empirical evidence on the impact of accessibility levels on desired outcomes including employment, good health, or overall activity participation. The definition of what an "adequate" level of accessibility or transport service means is ultimately as much a political decision as it is a moral one that deeply reflects the vision of a just city and mobility system each society aspires to build (Lucas et al. 2016b; Pereira et al. 2017). While defining an accessibility poverty threshold inevitably runs into challenges with paternalistic assumptions regarding individual preferences and needs (Cass et al. 2005; Preston and Rajé 2007; Vanoutrive and Cooper 2019), true sufficientarianism requires the definition of a normative reference point to use when assessing accessibility poverty.

Needs-gap and transit desert approaches

Among various methods available to examine transport poverty, an approach sometimes referred to as "needs-gaps" or "transit deserts" has seen widespread use. In general, studies in this tradition purport to quantify "gaps" between potential transit demand or accessibility needs, and some measure of public transit supply (e.g., proximity to transit stops and frequency) or access to opportunities by transit. The latter accessibility measures combine estimates of public transit supply or level of service with land-use measures to quantify how easily destinations can be reached. Locations where transit demand or accessibility needs exceed supply are sometimes referred to as "transit deserts" (Adler et al. 2010; Currie 2010; Delbosc and Currie 2011; Jiao 2017).

Limitations of needs-gap and transit desert approaches

Needs-gap and transit desert approaches found in the literature are incompatible with sufficientarian concerns for at least three reasons:

1. **Ignorance of local capacity**. The desert metaphor has been criticized, especially in the context of food access, both because it ignores residents' capacity to meet daily needs despite existing barriers and because it assumes that a new facility or service will *ipso facto* solve the problem regardless of whether it is tailored to local needs and preferences (Alkon et al. 2013; Hill 2017; Reese 2019). This criticism is also relevant to transportation access; people find less-than-ideal ways to meet their travel needs when alternatives are lacking (e.g., Blumenberg and Smart 2014; Burris and Winn 2006; Lovejoy and Handy 2011). Simply placing a new public transit route near a population will do little to address travel needs if it does not affordably serve desired destinations at convenient times. Additionally, the term obscures the historical and ongoing processes that created the food or transit "deserts" in the first place, including residential and workplace segregation, lending discrimination, and disparate infrastructure construction and funding patterns.
2. **Absence of normative thresholds**. Existing needs-gap studies are most often descriptive; they rarely explicitly adopt a reference threshold. Even when such thresholds are proposed, as in the case of "accessibility sufficiency" (Golub and Martens 2014) or "basic accessibility" (Vanoutrive and Cooper 2019), they are ad-hoc in that they are defined using below-average accessibility, public transit compared to automobile accessibility, or another arbitrary quantity. They imply no relationship between accessibility levels and desired outcomes including activity participation or well-being (Allen and Farber 2020; Luz et al. 2022). Part of the issue is that they presume that a sufficient level of service or accessibility can be deduced purely from the data or other technical criteria, without having to resort to normative principles. This supposed objectivity makes needs-gap and transit desert approaches appealing to both researchers and practitioners, but it also makes them inappropriate from a sufficientarian perspective.
3. **Use of fundamentally incommensurate supply and demand measures**. Measures of supply and demand used in needs-gap studies are mismatched—they do not capture similar enough concepts to ensure that calculated differences are meaningful. Because the units of supply and demand differ, authors often standardize them prior to calculating a difference (e.g., Currie 2010; Fransen et al. 2015). As a rule, because supply and demand are standardized, these applications assume that those quantities are balanced

when the difference is zero, but this assumption does not hold up under close scrutiny. There is no fundamental relationship between these standardized measures of supply and demand such that a one-unit increase in demand must be met with a one-unit increase in supply to minimize or eliminate gaps (Kaeoruean et al. 2020). Indeed, given the skew in the distributions of both population density and transit supply, the results often demonstrate that the locations in a city or region with the most robust public transit service are those that suffer from the largest gaps. For example, one study identified the entire Upper West Side in Manhattan as a transit desert (Jiao et al. 2021). The implication is that those locations need more transit service to be brought into balance, but what the result actually demonstrates is that the relationship between supply and demand is more complex than can be captured with simplistic indicators and standardized differences.

Alternative approaches for measuring accessibility poverty

In contrast to the relative nature of the needs-gap approach, a more promising alternative involves setting a normative accessibility poverty line and determining both the number of people below it and the size of the accessibility shortfall relative to it. There are different measures of economic poverty that can be or have been adapted to examine transportation poverty and insufficiency. The most popular is the Foster-Greer-Thorbecke (FGT) measure introduced in the 1980s (Foster 2006; Foster et al. 1984), defined in Eq. 3,

$$FGT_{\alpha} = \frac{1}{N}\sum\nolimits_{i=1}^{H}\left(\frac{z-y_i}{z}\right)^{\alpha} \tag{3}$$

where N is the size of the total population, z is a poverty line previously defined, H is the number of individuals below the poverty line z, y_i is the "income" or accessibility level of each individual i, and α is a parameter that determines how sensitive the index is to changes in the poverty gap.

Using Eq. 3, it is possible to compute three FGT indices that differ based on different α parameters. When $\alpha = 0$, FGT_0 measures the *extent* of poverty as a simple headcount—the proportion of people below the poverty line. For $\alpha = 1$, FGT_1 measures the *severity* of poverty as the average percent distance between the poverty line and the accessibility of individuals below it (a.k.a. the "poverty gap index"). The most-used FGT index in economics is the FGT_2. When $\alpha = 2$, Eq. 3 simultaneously measures the extent and severity of poverty by calculating the number of people below the poverty line weighted by the size of the accessibility shortfall relative to it. The value of FGT_2 ranges from 0 to 1, where 0 indicates that every individual is above the poverty line. When an entire population is below the poverty line, the values of FGT_1 and FGT_2 approach 1.

The FGT_2 was first used in the transportation equity literature by Martens (2016, p. 159). One of the advantages of FGT_2 is that it can be used to decompose the overall poverty level in a population into different subgroups. This decomposition allows one to compare the extent of transport poverty experienced by various groups and to determine how changing conditions would affect the overall poverty level.

A key characteristic of the FGT family of measures is that they require the poverty line to be defined a priori. Such a definition is both a moral and technical decision that would ideally take place among decision-makers and residents and be informed by robust causal links between marginal changes in accessibility and related effects on social, economic, and health-related outcomes. Unfortunately, the relevant political fora do not yet exist, and research with causal evidence on the links between accessibility and key outcomes is not well developed, with few exceptions (e.g., Bastiaanssen et al. 2022; Luz et al. 2022). These challenges can partially explain why FGT indices are still little used in the transport literature.

Data and methods

To demonstrate the limitations of Lorenz curve/Gini coefficient and needs-gap/transit desert approaches, we employ these methods and our proposed alternatives in an equity analysis of public transit service changes undertaken in the Washington, D.C. metropolitan area during the initial response to the Covid-19 pandemic. We compare two points in time: February and June 2020, representing a high point prior to the pandemic and the lowest levels of service experienced prior to a gradual increase that proceeded through 2020 (Karner et al. 2023).

Accessibility estimates

The public transit accessibility data used here were taken from a larger project—the TransitCenter Equity Dashboard (Klumpenhouwer et al. 2021). The data and methods used to prepare all of the accessibility estimates are open source and full methodological details are described elsewhere (Klumpenhouwer et al. 2021).

Here, our key performance measure is cumulative opportunities accessibility to all jobs within 45 min on public transit during the morning peak period (7am − 9am) at the census block group level, calculated using Eq. 4,

$$A_i = \sum_j O_j f\left(t_{ij}\right) \tag{4}$$

where A_i is the accessibility estimate for block group i, O_j is the total number of jobs located in block group j, and the impedance function $f\left(t_{ij}\right)$ returns one if t_{ij} <= 45 and zero otherwise.

Accessibility inequality and accessibility poverty

To operationalize accessibility inequality and poverty, we summarized our accessibility estimates over the entire region as well as for population subgroups. Specifically, we calculated Lorenz curves, Gini coefficients, Theil indices, Palma ratios, and concentration curves and indices using the methods described in the "Accessibility inequality" section. Socioeconomic data were taken from the 2014–2018 American Community Survey five-year estimates (ACS), focusing on the same census block groups used for the accessibility estimates. Some of the accessibility inequality results group block groups according to their population-weighted median household income deciles.

For accessibility poverty, we compared results generated using the typical needs-gap/transit deserts approach with those produced from the FGT measures. To operationalize gaps and deserts, we used our accessibility estimates to represent public transit supply and the count of people in economic poverty[3] to capture public transit demand. These supply and demand estimates were standardized to reflect the established practice adopted in the needs-gap literature. By focusing on those experiencing economic poverty, we highlight the importance of public transit for those with limited ability to afford other transportation options. Operationalizing supply and demand differently may yield different outcomes, but our aim is to emphasize the limitations of the dominant needs-gap methods used in the literature. To standardize the variables, we calculated z-scores and computed the difference between them using Eq. 5,

$$G_i = \frac{P_i - \mu_P}{\sigma_P} - \frac{A_i - \mu_A}{\sigma_A} \tag{5}$$

where i indexes block groups, G_i is the needs-gap—demand minus supply. If the difference is greater than zero, the method identifies a condition of undersupply. If it is less than zero, then there is a situation of oversupply. P_i is the number of people in poverty, and A_i is defined as in Eq. 4. Our FGT measures consider the poverty threshold to be the median population-weighted public transit accessibility across the region.

Study area

According to the 2021 one-year American Community Survey, the population of Washington, D.C. was 670,000, while the population in the greater Washington-Arlington-Alexandria metropolitan area was approximately 6.4 million people. Our study area encompasses the "urban core" of the region, an area developed by TransitCenter in consultation with local public transit advocates. It is intended to capture places where public transit is most viable, based on population density, existing commute flows, demographics, and the existence of high-frequency transit service.

The Washington Metropolitan Area Transit Authority (WMATA) delivers multimodal transit services, including heavy rail, BRT, local bus, and paratransit. Like many transit agencies worldwide, WMATA faced a significant ridership decline during the Covid-19 pandemic and adjusted its services accordingly. By April 2020, service intensity dropped by approximately half compared to pre-pandemic levels in February 2020 (Karner et al. 2023). Weekday ridership plummeted from 640,000 in February to 36,000 in April 2020 (Sablik 2023).

Figure 2 shows heavy-rail alignments alongside socioeconomic and transportation-related conditions throughout the region. There is clear evidence of residential segregation by race, and households in poverty concentrate in the same locations as Black and Latino residents. Zero-vehicle households tend to be located within the District of Columbia proper, but throughout the region there are scattered high shares of people commuting by modes other than driving alone.

[3] Poverty status is defined by the U.S. Census Bureau using income thresholds established separately for households in different size/income categories (Census Bureau 2023).

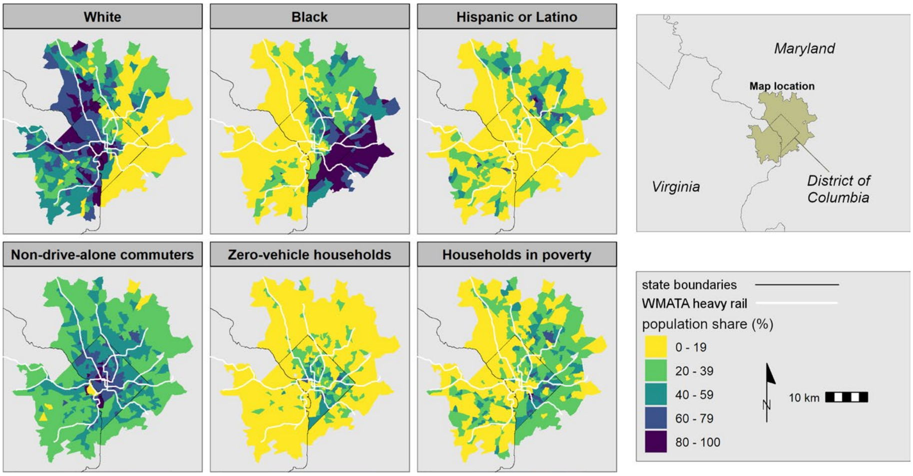

Fig. 2 Washington metropolitan region urbanized area demographics sourced from the American Community Survey 2014–2018 five-year estimates

Results and discussion

Overall Covid-related impacts

Service cuts had a dramatic impact on accessibility. Figure 3A shows overall transit accessibility to jobs in February 2020 and at the depths of service reductions in June 2020. Changes in accessibility show severe losses throughout Virginia, Maryland, and the district itself (Fig. 3B). Northern Virginia—with relatively high concentrations of white residents and low concentrations of people in poverty—sustained heavy accessibility loses. However, visual assessments and comparisons are hardly definitive. In the subsequent sections, we systematically assess how accessibility inequality and poverty change using multiple metrics and approaches.

Lorenz curve and Gini coefficient

Figure 4 summarizes the impact of accessibility changes using Lorenz curves and Gini coefficients. The overall Gini coefficient increases from 0.54 to 0.59, suggesting that inequality worsens overall. Additionally, the Gini coefficients calculated for each decile also worsen, indicating that conditions *within* each decile become less equal after the service cuts. Importantly, these metrics do not provide information about inequalities between income groups. The increase in the post-Covid Gini coefficient demonstrates that inequality increases overall, but it does not tell us whether this shift results from a growing gap between deciles 1 and 10 or from changes between more closely positioned groups.

Theil index

Like the Gini coefficient, the Theil index suggests an increase in overall population-wide inequality, increasing from 0.49 to 0.61 (Fig. 5). But unlike the Gini coefficient, it is

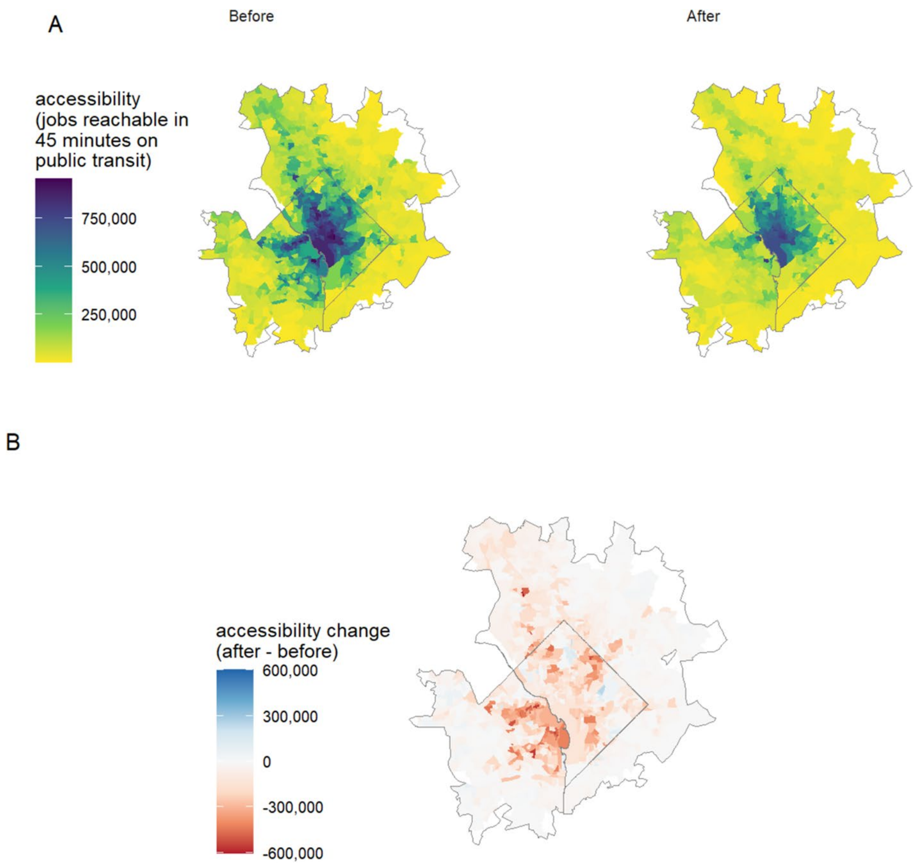

Fig. 3 Spatial distribution of (A) accessibility levels before and after the service cuts, and (B) changes in accessibility due to service cuts

possible to decompose the Theil into within and between group inequality. We find that the service cuts increased both types of inequality, although increases in within-group inequality dominate, comprising 94% of the total inequality. Only the remaining 6% is due to inequalities between income groups. Practically, this result means that there are greater disparities in access scores within each decile but that average conditions across deciles are more similar. It is important to remember that the Theil index, like the Gini coefficient, does not perform a comparison between ordered groups. This means that the between-group inequality from Theil considers all groups simultaneously. As such, it is not clear from the Theil index whether the increase in between-group inequality occurred due to increasing inequalities between the poorest and the wealthiest deciles, or between adjacent income groups.

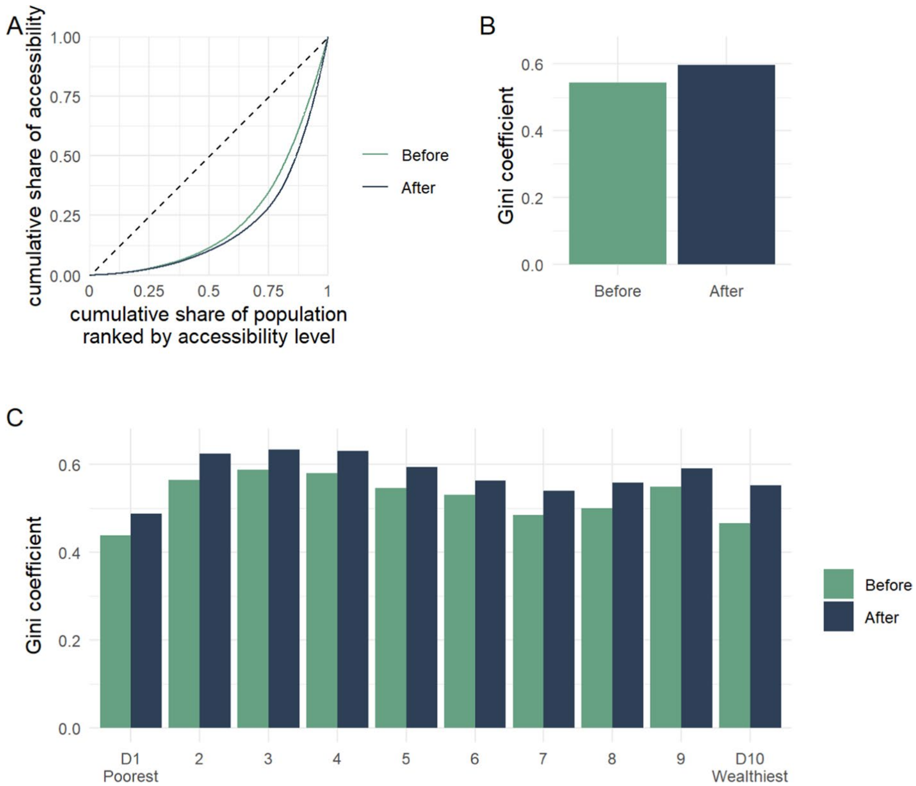

Fig. 4 Gini coefficient and Lorenz curve results summarizing **A** Lorenz curves for the entire population, **B** Gini coefficients across the entire population, and **C** Gini coefficients for each income decile, before and after service cuts

Palma ratio

In contrast to Gini and Theil, the Palma ratio considers how groups are ordered. The results show that the Palma ratio drops from 1.33 to 1.2 after the service changes. Prior to the Covid-19 pandemic, the wealthiest groups had on average 33% higher accessibility than the poorest. Service cuts reduced this inequality to 20%. In contrast to the Gini and Theil results, the Palma ratio suggests reduced inequality.

These results also demonstrate that understanding context and evaluating changes is key to meaningful interpretation of the measures. In this case, the reduction in inequality comes against the backdrop of dramatic service changes. While it is notable that they do not fall disproportionately on low-income people, the simple decrease in the Palma ratio should certainly not be considered a transportation equity win. While inequality has decreased, this has surely been accompanied by many low-income residents seeing worsening services.

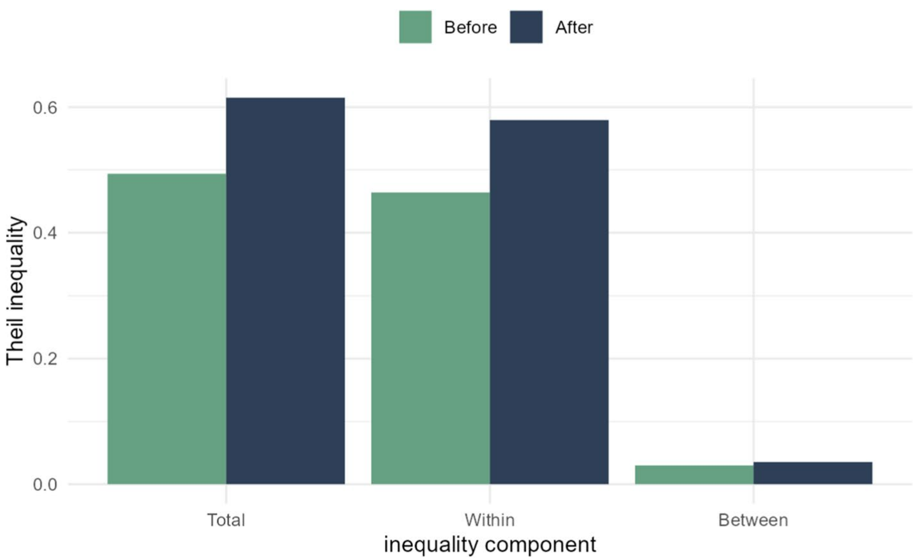

Fig. 5 Theil index before and after public transit service changes

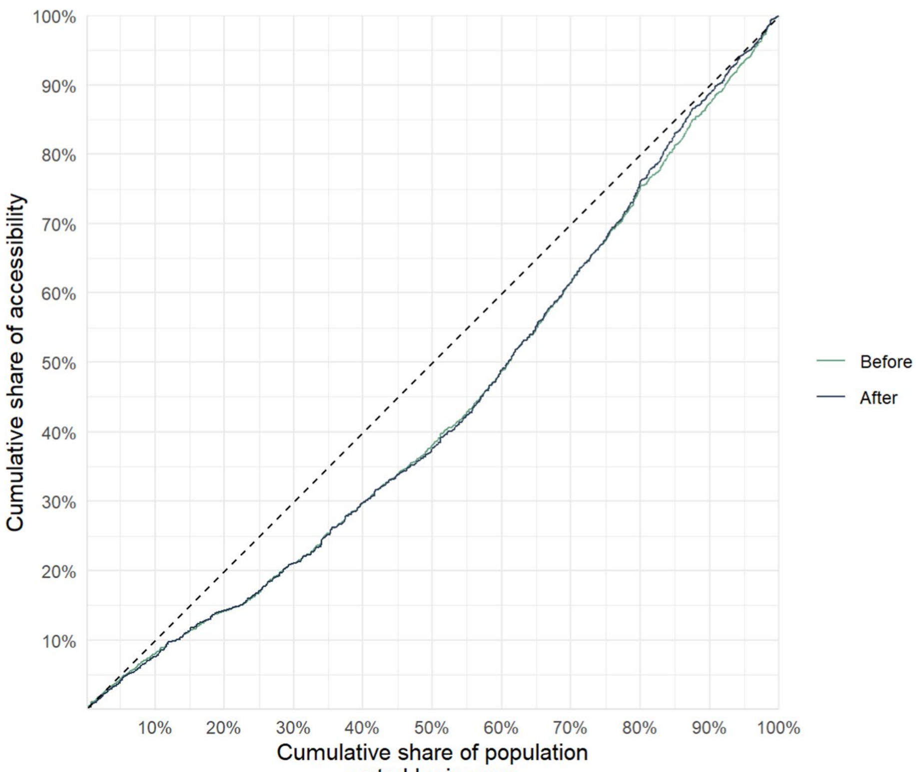

Fig. 6 Concentration curves of accessibility scores sorted by the median income of block groups before and after service cuts

Concentration index

Like the Palma ratio, the concentration index shows a reduction in accessibility inequalities, but it is much smaller in magnitude. The overall CCI changes from 0.10 to 0.08, suggesting that Covid-related service changes had a progressive but very small impact on inequality. This small change is apparent when looking at concentration curves for the two periods (Fig. 6). They show that the socioeconomic distribution of access to opportunities remains largely the same before and after the service cuts. The changes most notably affect upper-income groups. Block groups with the highest 15% average incomes saw their cumulative share of accessibility drop almost 2 percentage points, from 18.7 to 17%. The bottom 50% of block groups saw their share of total cumulative accessibility drop slightly by about 0.4 percentage points. Overall, slight drops in accessibility for high-, middle-, and low-income groups are redistributed throughout the rest of the population with the net result that overall inequality is somewhat lessened after the cuts.

Overall takeaways

These contradictory results highlight that it is crucial to make conscious methodological choices when analyzing transport inequalities. Depending on the indicator used, one could conclude that accessibility inequalities increased (Gini and Theil), decreased (Palma), or decreased only slightly (CI), due to Covid-related service cuts. These apparent inconsistencies are a consequence of the characteristics and limitations of the indicators used here. Although both Gini and Theil point to an increase in overall inequality, they fail to capture the extent to which observed inequalities and changes in inequality levels are systematically related to socioeconomic conditions. As a consequence, these indicators are at odds with equity/egalitarian concerns, as they cannot determine whether accessibility inequalities (mere differences between groups) are also access inequities that tend to benefit better-off groups at the expense of others, or vice versa.

In contrast, the Palma ratio and CI are better able to reflect egalitarian concerns by comparing inequalities between groups ordered by socioeconomic levels. These indices capture not only whether a given distribution is more concentrated among disadvantaged or well-off groups, but also whether the direction of changes in inequality favor the poor or the rich. However, because the Palma ratio overlooks inequalities within groups and excludes middle-income individuals from the comparison, it presents a limited picture, which in our case likely overestimates inequality levels. When using the CCI, a ranked inequality measure that accounts for the full distribution of individuals' accessibility and income levels, we obtain a more complete and nuanced understanding of transport inequalities and policy impacts.

Changes in accessibility poverty

Needs-gap analysis

Figure 7 shows the location of areas of undersupply (deserts) and oversupply (not deserts) relative to potential demand before and after the major service cuts undertaken by WMATA. Summary demographics and block group characteristics are shown in

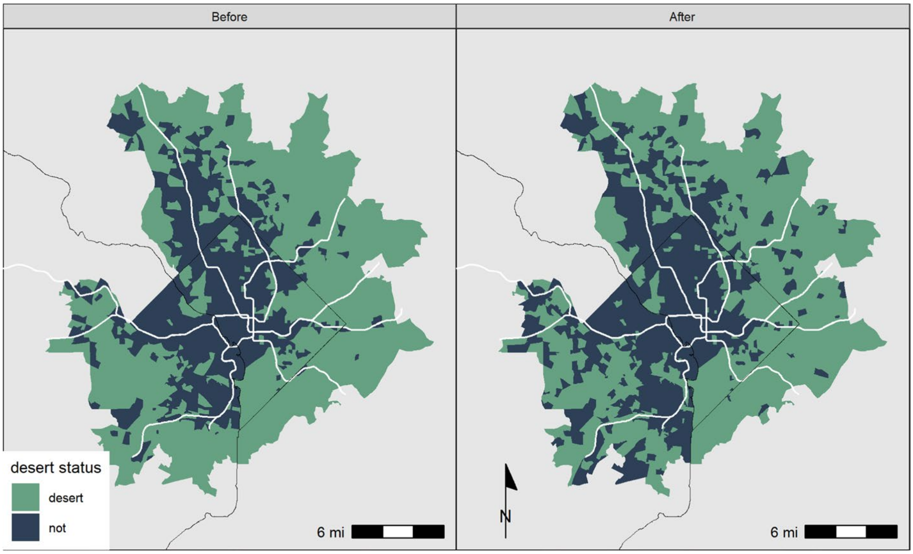

Fig. 7 Transit deserts before and after service changes

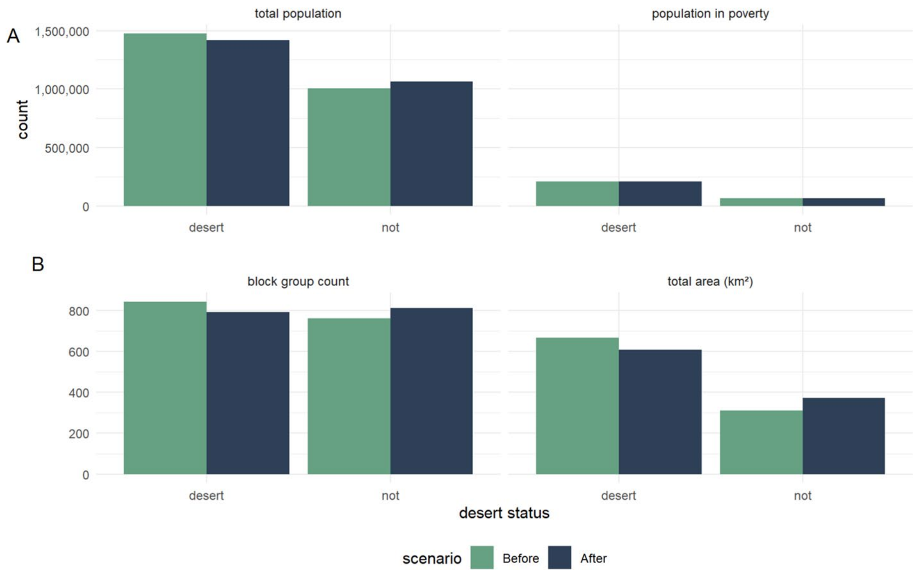

Fig. 8 Changes in block group **A** total population and population in poverty and **B** count and total area by desert status before and after service cuts

Fig. 8. Counterintuitively, the spatial extent of the deserts *shrinks* during the time at which public transit service in the region is the lowest (Figs. 7 and 8B). Indeed, the number of people residing in deserts decreases by about 60,000 or 5% when public transit service is objectively much worse across the region (Fig. 8A). This outcome is

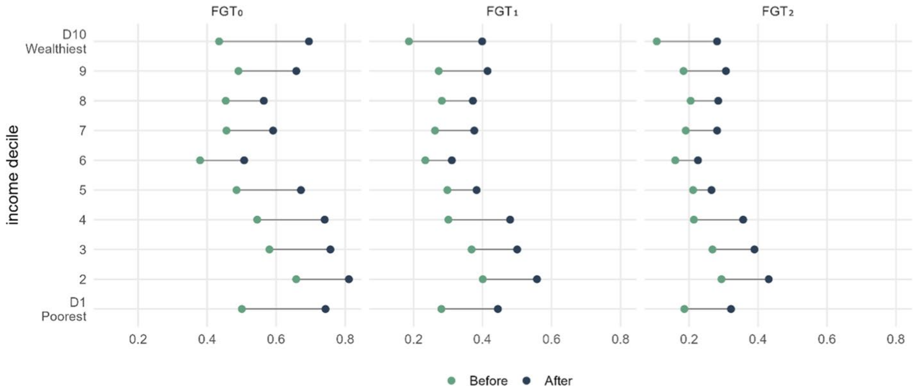

Fig. 9 FGT sufficiency indicators before and after 2020 service changes using the 50th percentile public transit accessibility as the relevant threshold

possible because the method used for quantifying gaps is normalized, giving relative estimates within a single cross-section in time. These do not provide meaningful comparisons across time periods. If transit accessibility was reduced uniformly by 50% within every block group, the needs-gap assessment would not change at all. In the case of this Covid-related cut, patterns of accessibility shifted such that fewer block groups showed a gap that exceeds a standardized difference of zero after the service change was implemented. Substantively, this result does not mean that fewer people faced accessibility poverty in June compared to February 2020.

These results call into question the face validity of transit desert calculations that are based on relative measures of demand and supply. This is not a contrived example. These data reflect actual service cuts that WMATA undertook and our best faith efforts to recreate the needs-gap methods employed in the literature over the past 20 years. As this comparison shows, we simply cannot rely on needs-gaps to provide meaningful information about the extent to which public transit is serving riders at a point in time or as service inevitably changes.

One way to minimize the limitations of the needs-gap method would be to standardize supply and demand considering their distributions in both periods (before and after) simultaneously. This approach would mitigate the problem of not capturing changes in service levels. We completed a needs-gap analysis that standardized the service levels in June using the mean and standard deviation from February (results not shown). As expected, conditions worsen—more block groups are identified as experiencing a service gap and a greater total population and population in poverty experience these conditions. If conducting a before and after needs-gap analysis, this approach would certainly be more meaningful than standardizing by the service levels within each period. Nonetheless, needs-gap assessments are almost always undertaken at a single point in time. We have demonstrated that it is possible for objectively worse transit service to result in fewer identified service gaps. At a single point in time, it is not possible for the analyst to know whether the gaps they observe are due to objectively poor service or the vagaries of a particular standardized distribution. Additionally, even this fix identified here does not overcome the critical limitation of comparing supply and demand based on incommensurable units or other limitations discussed in the "Accessiblity poverty" section.

Sufficiency analysis

A more promising approach to examine accessibility poverty is to use the FGT family of indices. For this application, we have set the relevant poverty threshold using the population-weighted 50th percentile of public transit accessibility in the urbanized Washington D.C. metropolitan region in February 2020. Figure 9 summarizes FGT indicators for income deciles calculated separately for February and June 2020. Higher FGT values are objectively worse; they indicate conditions where larger numbers of people fall below the threshold, the distance between actual conditions and the threshold is larger, or both.

The results are unambiguous. For all income deciles, the number of people in accessibility poverty increases after the cuts. According to FGT_0, the hardest-hit groups are the lowest and higher income deciles—they both see a 25-percentage-point increase in the number of people experiencing accessibility poverty. When considering the intensity of shortfalls between accessibility levels and the threshold (FGT_1 and FGT_2), similar patterns hold. Accessibility poverty tends to be more pervasive and more severe among low-income groups (particularly between income deciles 1 and 4), and accessibility poverty increases after the cuts across all income groups, but especially at the highest decile. These results demonstrate a critical face validity that is lacking from the current needs-gap literature. In other words, the direction of changes in the FGT metrics comport with our a priori understanding of how they would be expected to shift when service is reduced.

In summary, examining Covid-related service changes shows that needs-gap analyses result in counterintuitive findings in which conditions apparently improve following a major service cut—fewer people reside in areas identified as experiencing insufficient service. On the other hand, the FGT indicators demonstrate consistently that all groups experience worse sufficiency after the cut.

Conclusions

Determining whether a transportation system or policy is equitable is not straightforward. Different equity definitions emerge from different moral principles. Two dominant principles exist in the literature and practice: egalitarianism and sufficientarianism. Egalitarianism focuses attention on mitigating accessibility inequalities. Sufficientarianism focuses on accessibility poverty, examining the extent to which people experience accessibility levels that do not allow them to meet daily needs. In this paper we have critically reviewed Lorenz curves/Gini coefficients and needs-gap/transit desert approaches, the most widely used approaches to quantify accessibility inequality and poverty, respectively. Although these methods are intuitively appealing, their fundamental assumptions and outputs render them incompatible with those originating from moral political philosophy. They also fail the critical test of face validity. Alternatives are needed.

When measuring accessibility inequality, the Palma ratio and the concentration index are preferred because they address each of the five limitations inherent in Lorenz curves and Gini coefficients. By basing their calculations on comparisons between socioeconomically ordered groups, they identify whether better or worse off groups enjoy disproportionate benefits at baseline or after a policy intervention. Understanding which groups benefit and to what extent is more consistent with egalitarian concerns. In our study of public transit service cuts, measures that account for socioeconomic ordering generated opposite findings compared to those that do not.

Accessibility poverty, undergirded by sufficientarian concerns, can be a powerful framework for understanding the extent to which specific population groups are likely to be constrained in meeting their daily needs. We demonstrated that popularly employed needs-gap methods can produce illogical results when calculated for a service cut scenario. This outcome calls into question their use of incommensurate measures of transport supply and demand. As an alternative, we calculate the family of FGT metrics using the median population-weighted public transit accessibility as our poverty line. These metrics do not compare supply and demand; rather, they count and optionally weight the number of people experiencing a certain shortfall. They performed much better by providing more information on both the extent and intensity of accessibility poverty, and yielded results that were consistent with common-sense understandings about how accessibility poverty should change when transit services are cut. The FGT measures do not solve the problem of choosing an appropriate threshold of sufficient access. But once such a threshold is identified, the FGT measures offer a simple and intuitive solution for operationalizing it and evaluating transport poverty's extent and severity.

We understand that the definition of a minimum acceptable level of accessibility is context-dependent and that it should be established based on vigorous public debate and political participation. But the literature lacks robust work on the link between accessibility and well-being in terms social, health, and economic outcomes, as well as participation in out-of-home activities. Once we have solid evidence of these relationships, a baseline of minimum accessibility could be defined through informed political debate that reflects a vision of a just city and mobility system at an appropriate scale. FGT measures can incorporate this threshold, while needs-gap approaches, as previously conceived and applied, cannot.

Our work has focused on key technical questions related to measuring transportation system benefits and burdens, with a particular focus on questions of distributive justice. Distributive justice is necessary but not sufficient for a full accounting of mobility justice. As enumerated by Sheller (2018), mobility justice encompasses questions of process and deliberation, whose knowledge is able to shape decision-making, and the extent to which policies address historical and ongoing harms. The FGT measures we employ to assess sufficiency, for example, still ignore the local capacity to meet needs in the face of state and procedural neglect. Indeed, much of the work on transportation equity summarized here is vulnerable to the critique that it leaves out important dimensions of access and justice by focusing largely or solely on distributions. All distributional analyses will leave out critical dimensions while treating others only partially. And no distributional analysis will be enough to move the needle on real-world equity conditions on its own if is not grounded in the needs and concerns of the groups it is meant to represent as well as the political and historical processes that create and maintain inequities. Such an analysis would also need to be connected to broader political movements and able to meet some moment where change is possible. That said, thinking critically about the analytical methods used in the transportation equity literature and practice can help expose shortcomings and make recommendations for improvements. Better methods in this case would more closely reflect the real-world transportation conditions that people face.

Author contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by A.K. and R.P. The first draft of the manuscript was written by A.K. and R.P. and all authors commented on subsequent versions of the manuscript. All authors read and approved the final manuscript.

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Data availability Scripts and data necessary to reproduce the results are available on Github: https://github.com/aakarner/transit-equity-methods. All poverty and inequality metrics discussed in this paper have been implemented in the {accessibility} package in R (Pereira and Herszenhut, 2022) to facilitate their use by other researchers.

Declarations

Competing interests The authors declare no competing interests.

Ethical approval This section is not applicable because this work did not involve human subjects.

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