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Fair accessibility – Operationalizing the distributional effects of policy interventions

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ABSTRACT

A fair distribution of public transport benefits is a commonly stated goal of agencies and operators of public transport. However, it is less complicated and costly to provide accessibility in some parts of cities and their surroundings than in other parts. Densely populated areas, and areas situated closer to the city center therefore often have higher public transport accessibility than remote or sparsely populated areas. Neglecting these realities results with an unrealistic assessment of equity in service provision and hampers their consideration when setting policy goals. In this study, we propose a framework for investigating equity in the distribution of accessibility, where the suggested goal is to provide residents with equal accessibility for equally dense and central areas. For the Stockholm County, we show that accessibility may seem to be distributed horizontally inequitable and vertically regressive. However, once controlling for how dense and close to the city center residents live, while still being horizontally inequitable the distribution of accessibility in Stockholm County is found progressive, i.e., benefiting those with lower incomes. We demonstrate the proposed method for the case of skip-stop train operations and find that it shifts our constructed accessibility measure toward a more horizontally inequitable and vertically progressive state. We conclude that our proposed method can be a potent way for public transport agencies to measure and concretize equity goals and evaluate policy changes.

1. Introduction

Access to activities is a core need for all, and the fair distribution of accessibility is directly impacting society's capacity to reach several of the UN global development goals. Scholars have contributed to the understanding of justice in the area of transportation (Martens, 2016) and endeavored to list and to comprehensively assess the state of inequality in transport (Lucas, 2012; Banister, 2018). A fundamental measure of transportation quality is the accessibility. Measures of accessibility are commonplace in the literature (Minocha et al., 2008; Delbosc and Currie, 2011; Golub and Martens, 2014). An implicit assumption for most of these measures is that the measured distribution of accessibility should be compared with ideals of giving all citizens the same accessibility (combined with eventual compensation to certain groups defined as vulnerable or with particular needs).

Providing public transport with the same accessibility and performance for all citizens is practically infeasible in all but very generalized and simplified cases. In all actual cities, land use patterns, network geometry, and economies of scale make it very expensive to provide the same level of accessibility to all. It is even questionable if this is a desirable goal to have, given the significant differences in production cost per accessibility unit in different parts of the network. Substantial factors, such as a concentration of attractive destinations and population density, impact the level of public transport accessibility. We argue that these factors are legitimate reasons for differentiation in accessibility provision. To date, there is a large body of literature on how to measure accessibility and compare distributional impacts. However, few studies discuss the practical implications of striving to attain a fair distribution of public transport accessibility in the face of providers' limited ability to achieve the same accessibility for all.

In this study, we present a framework for assessing the equity of

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accessibility provision while taking such legitimate factors that warrants differentiation into account. We compare actual accessibility with a sought after state, which we refer to as *target accessibility* where only a few selected, legitimate, factors impact accessibility. We measure the accessibility with logsums from a trip destination choice-model, taking generalized travel costs, and the quality and distribution of destinations into account. We then construct the target accessibility as a function of origin population density and closeness to the center of gravity of the urban agglomeration. We deem these factors legitimate for differentiation since origin density gives economic grounds for high-frequency provision of services, and closeness to the central region is a fitting proxy for proximity, and thus low generalized travel cost, to a high number of destinations. The specific formulation of the target accessibility is achieved by performing a linear regression of the logsum accessibility as the dependent variable and the two chosen factors as independent variables. We then study the residual between actual and target accessibility as the distribution of unwarranted inequality. We assess horizontal and vertical inequities, i.e., how uneven the residual accessibility is distributed among all residents and whether this distribution benefits high or low-income residents. The Equity measurements are made with Lorenz curves and polarization Gini (Raffinetti et al., 2015) as well as an original development of polarization Suits, building on the Suits coefficient (Suits, 1977). Finally, we demonstrate our approach by evaluating an introduction of skip-stop services on the Stockholm commuter train network. This policy measure was proposed to improve remote areas accessibility with shorter travel times at the expense of more central but less densely populated and more affluent areas.

The remainder of this paper consists of the following. In Section 2 we review the literature on equity and accessibility, then we describe our method in Section 3, and in Section 4, we present our application and results. Finally, in Section 5, we offer our conclusions and recommendations.

2. Literature overview

In this literature overview, we focus on discussing the different methodologies used to capture accessibility, rather than the findings reported by individual studies. We start by looking at the balancing between accessibility measures that are comprehensive but complex versus measures that are more intuitive but might fail to capture some effects. We compare different measures positioned along this spectrum. Then we look at the literature that combines measuring accessibility and assessing equity effects. Finally we review the literature on the trade-off deliberations the policymaker needs to perform between accessibility, equity, and other operational and efficiency concerns. In this study, we refer to the notions of horizontal and vertical equity, commonly used in the literature. Horizontal equity refers to equity among equals, all getting their fair share. Vertical equity pertains to equity among unequal's, where equity is assessed between groups formed by some socioeconomic characteristics that might impact group members' need for or use of public transport, such as income, car ownership, age, and activity status. E.g., horizontal equity can refer to residents (irrespective of socioeconomic status) having an equal walking distance to their first public transport stop. In contrast, vertical equity compares if low-income residents as a group have equal walking distance as high-income residents.

In their review of accessibility, Geurs and Van Wee (2004) show how an accessibility measure should include several relevant criteria to give a full assessment, such as the configuration of the transportation system, the distribution of homes and activities, the temporal and economic constraint on trips. Further, they indicate the variation of accessibility over the peak and off-peak hours, the competition for activities (e.g., if accessibility is measured for more job-seeking residents than available jobs), and variation in the ability to use the transport system over the population. Such a full assessment can be both unattainably complex to compute and impossibly hard to communicate. Geurs and Van Wee (2004) conclude that it can be sufficient to be aware of the multifaceted nature of accessibility while still choosing a less complicated measure to assess problems where one believes that the selected measure, understanding its limitations, captures the essential or knowable difference.

There are a few common variations off accessibility measures, limiting some of the relevant criteria enumerated above, in the literature. One such measure is Coverage-accessibility, where the share of potential passengers served by stops and the quality or frequency of services for those stops are measured (Delbosc and Currie, 2011). Contour-measurements list how many activity-destinations (e.g., workplaces) are reachable inside a pre-defined travel time limit (Golub and Martens, 2014; Banister, 2018). Gravity-modeled accessibility, measures that weigh generalized travel cost to all possible destinations with the number, or quality, of activities possible in those destinations (Minocha et al., 2008; Owen and Levinson, 2015).

The equitable distribution of accessibility is at the core of the literature regarding transport justice (Martens, 2016). The literature on equity aspects of accessibility shows examples of both horizontal and vertical equity. Lucas (2012) and Banister (2018) powerfully argues that it is of high importance to consider the compounding effects of various factors in assessing the situation for the most disadvantaged looking at, e.g., poverty, disabilities, economic and social exclusion, disposable time and unemployment. It could be inferred from this that sophisticated measures or combinations of measures to describe accessibility are preferable when capturing vertical equity. In contrast, horizontal equity might be monitored with more straightforward accessibility measures. In practice, most assessments of equity use a combination of a limited accessibility measure and some evaluation on the travel and residential patterns of different population groups to capture vertical equity aspects.

Delbosc and Currie (2011) use Lorenz curves and Gini-coefficients to describe the horizontal equity of (coverage) accessibility and combining this approach with census data on age and income to describe the vertical equity. In an assessment of vertical equity, Cui et al. (2019) show how changes in (gravity-modeled) accessibility, with competition taken into account, have a higher impact on work commute patterns for low-income travelers' than on high-income travelers. Minocha et al. (2008) use an unusual combination to compare a coverage accessibility measure to a gravity-based model over workplace accessibility. They then rank census areas in both regards (horizontal equity) and look at the composition of census area populations' income and car-ownership to assess ranking for these socioeconomic groups (vertical equity). Golub and Martens (2014) define access-poverty as the quota between car and public transport (contour measured) accessibility. They then use that measurement as an assessment on proposed policy shifts (does the shift increase or decrease the access poverty) and, using census data, computes vertical equity effects for low-income and minority residents. Transit deserts are another vertical equity approach to accessibility in the literature. The distribution of transit-dependent populations is compared with the distribution of public transport supply and significant discrepancies, with a high concentration of transit dependence in combination with low levels of public transport supply is identified as transit deserts in need of policy improvement (Jiao and Dillivan, 2013; Jiao, 2017).

However, for the policy planner, equity is not the sole concern. There are also other quality and performance factors involved in the provision of accessibility and its distribution. How should the public transport system work, and what targets should it meet? Apart from providing horizontal and vertical equity, the transportation system should operate efficiently with an acceptable level of farebox recovery. It should also offer a reliable alternative for car traffic in the most congested parts during peak hours. Proposed policy shifts should be recommendable from a CBA point of view as well as from an equity point of view. As reported above, Golub and Martens (2014) provide an example of how to evaluate a policy proposal in the latter sense. Another approach is provided by (Wei et al., 2017), solving the combined problem of maximizing operational efficiency and maximize public transport stops coverage (coverage-accessibility) of several disadvantaged groups (elderly, children, carless households, unemployed, disabled, poor, non-white).

However, the intersection between equity evaluations on accessibility and their use in day-to-day policy planning is still underdeveloped. In this study, we propose a way of addressing the horizontal equity of accessibility given the nature of public transport as well as a methodology to assess horizontal and vertical equity of proposed policy measures.

3. Methods

The premise of our proposed methodology is that some differences in public transport accessibility are warranted. In particular, if there are many people residing in proximty and/or if many attractive amenities are situated nearby, then more people can be expected to benefit from it and the marginal cost of providing public transport accessibility drops. These circumstances that decrease costs and improve public transport's ability to compete with cars arguably provide legitimate grounds for differentiation in provided accessibility. But there are also, plausibly, many other factors that might not be legitimate or costly to remedy. To discern these legitimate from illegitimate factors, we construct a target accessibility, dependent on only the legitimate factors. Then, the difference between this target accessibility and the actual accessibility yields the pertinent equity effects to assess and maybe, for the planner, to counteract.

In Section 3.1, we describe the target accessibility. To measure accessibility, we use the logsums measure, which is complex but has the advantage that it can be converted into monetary terms, giving the policymaker an increased ability to weigh policies and the costs thereof against their effects. We describe the logsum measure in Section 3.2. Finally, to examine the accessibility distribution, we use Lorenz curves, and, for the horizontal and vertical equity assessments, the scalar measures Gini and Suits, which are described in Section 3.3.

3.1. Target accessibility

We need the target accessibility to include a set of selected factors considered to be relevant for the fair allocation of service accessibility. This target accessibility is used to determine which differences in accessibility the policymaker should examine closer. In Fig. 1, we illustrate a schematic version of the target accessibility compared with the actual accessibility. In this example there are four areas A-D with differing actual accessibility (vertical axis) and differing levels of legitimate factors x (horizontal axis). The dotted line represents the target accessibility, the fair distribution of accessibility given a set of factors x. If the areas' accessibility depends solely on the legitimate factors, they would be on the dotted line, but this is only the case for area C.

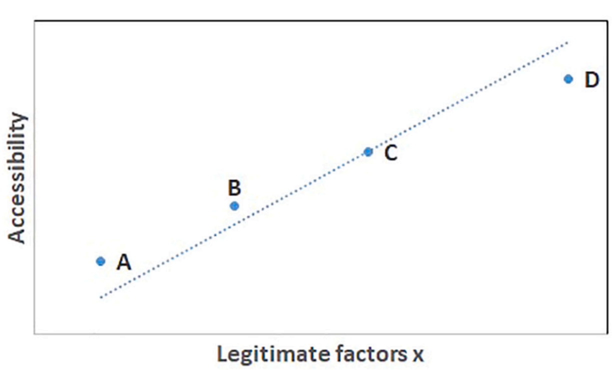

Fig. 1. Target accessibility as a function of legitimate factors x (dotted line) vs. actual accessibility (points A-D).

Therefore, in our analysis, accessibility is inequitably distributed with residents in area D being disadvantaged and residents in areas A and B having an undue advantage. If area D is an area with a lower median income than A and B, then there is also a vertical inequity in the accessibility distribution.

We construct the target accessibility by means of estimating a linear regression model where the actual accessibility is the dependent variable, and the independent variables are a set of selected factors considered to be relevant for the fair allocation of service accessibility. We then consider the errors, i.e. the distance between individual points and estimated regression line, as discrepancies between the actual service accessibility in a given zone and the target fair level. A distributional instance that result with smaller discrepancies (errors) correspond then to an increase in equity.

In this study, we define two factors that should arguably have an impact on public transport accessibility. The first factor is closeness to the center of gravity of Stockholm County, i.e., Stockholm Central Station (the region's central business district). The second factor is the trip-origin area population density. We reason that centrality is a good proxy for high density of attractive destinations close by (since in general the more central the location, the more compact the land uses are) and that origin density is a strong economic rationale for providing high-frequency services, hence leading to a reduction in the marginal cost of service provision. The specific mathematical formulation of the target accessibility may vary. In this study, we perform a simple linear regression with the actual accessibility as the dependent variable and our set of selected factors as the independent variables. We present this regression analysis in Section 4.3.

3.2. 'Logsums' as measures of accessibility

Logsums are the sum value of the utilities associated with a set of choices available to the decision maker. If the choice set consists of all possible destinations, the Logsum may express the accessibility with public transport (the sum value of choices among all possible destinations). The logsum offers an important advantage for planners being a byproduct of the standard four-step transport model. That means that if a planning agency has access to such a transport demand forecast model, then the logsums are directly extractable.

In the multinomial logit (MNL) destination choice model, it is possible to interpret the logarithm of the denominator ("the logsum") as a measure of the expected consumer surplus, E(SC), of the choices present in the model. Specifically, if the MNL model is used to obtain the probability of choosing a destination from a set of destinations based on generalized travel costs and relative attractiveness of the destinations, then the E(CS) can be interpreted as a measure of accessibility. This logsum can be expressed in monetary terms if divided by the marginal utility of money (De Jong et al., 2007): assuming that, α = marginal utility of money

$V_j = utility\ of\ choice\ j$

$C = unknown\ constant$

$$E(CS) = \left(\frac{1}{\alpha}\right) ln\left(\sum_j e^{V_j}\right) + C \tag{1}$$

Due to the constant, it is not possible to assess the exact level of consumer surplus/accessibility. However, our interest lies not in the absolute accessibility level but in its spatial differences as well as how those are manifested with and without policy interventions. Consequently, when calculating differences, the constant cancels out, and the change in consumer surplus can be measured.

In the following, we utilize the Swedish national MNL-model, starting with the accessibility for public transport trips to go to work. The utility to work for residents in zone *i* using public transport is the sum of the utility for all destinations j reachable from origin i:

x_{rij} = transport utility components (cost, time etc) between zones i to j

S_j = attractiveness of destination j

$$V_i = \sum_j V_{ij} = \sum_{rj} \beta_r x_{rij} + ln(S_j) \quad (2)$$

In the present model, there are 12 distinctive trip purposes with different functions of attractiveness measures, the second part of the equation above – $\ln(S_j)$. When investigating how the function differs for different trip purposes, we find that the differences in accessibility stemming from difference in service attributes (cost, time, etc.) are orders of magnitude larger than the differences stemming from different trip purposes. Therefore, to maintain a lean description and analysis we omitted the information on differences in accessibility by trip purpose. We therefore focus in the remaining of this study on the analysis of accessibility for work trips.

$S_j = wp_j$ = number of workplaces in zone j

c_{ij}^{pt} = public transport fare cost between i and j

t_{ij}^{pt} = percieved public transport journey time between i and j

δ_j^{mc} = dummy which is 1 if the destination is part of a municipal center

d_j = population density in the destionation

$$V_{ij} = -0.758 - 0.019c_{ij}^{pt} - 0.014t_{ij}^{pt} - 0.275\delta_j^{mc} + 0.000004d_j + ln(S_j) \quad (3)$$

From Eq. (3), we see that the marginal utility of money is 0.019. The dummy variable for municipality centers is there to model external localization of workplaces, decreasing the utility of a destination as a workplace destination if it is a municipal center. The population density models the propensity to use public transport rather than a car in dense areas due to congestion and parking constraints.

3.3. Equity measurement

We use (i) the Lorenz-curve (Lorenz, 1905) to examine the distribution of accessibility, (ii) the Gini (Gini, 1912) scalar, to obtain a single value reflecting the unevenness of the distributions and (iii) the Suits (Suits, 1977) scalar to provide a value on how progressive or regressive the distributions are. There is a large body of literature on the Gini coefficient, conceptualized by Gini (1912) with derivations by (Atkinson, 1970; Sen et al., 1997), and previous applications in the transport context (Delbosc and Currie, 2011; Welch, 2013; Nahmias-Biran et al., 2014; Jang et al., 2017).

Fig. 2 shows two versions of the Lorenz-curve. The Lorenz curve show distribution of some benefit over a population. The population, ordered by some metric (x-axis) versus the accumulated benefit share (y-axis). The Lorenz-curve, L(x), is then the accumulated share of the benefit that the bottom x percent of the population has. When everybody has the same amount of the benefit, the Lorenz-curve will trace the dotted diagonal. If the population is ordered by how large share of the benefit they have, so that percentile x always has equal or less amount of the benefit than percentile $x+1$, then the Lorenz curve shows the inequality of how the benefit is distributed (left-hand side of Fig. 2). With the population ordered in this way, the Lorenz-curve can be used to calculate the Gini-coefficient. The Gini measures how unequal the distribution is, with value 0 when it is equal (everybody has the same amount) and 1 in total inequality (top percentile has all of the benefits). If, on the other hand, one orders the population by increasing income, having the poorest at 0 and the richest at 100, then the Lorenz-curve can be used to calculate the Suits-coefficient (right-hand side of Fig. 2). The Suits coefficient also looks at inequality, but in contrast to the Gini, it also checks if eventual inequality benefits low-income or high-income residents. It ranges between -1 (all benefits to the poorest percentile) over 0 (perfect equality) to 1 (all benefits to the percentile with the highest income).

So, the two scalar values help to order different distributions in more or less equal and more or less progressive, respectively. The distribution as a whole can be better understood by also studying the Lorenz-curves. Both types of Lorenz-curves start and end at the same points. For each part of the Lorenz-curve, one can compare the inclination of the curve with the inclination of the dotted diagonal. If the Lorenz-curve is steeper than the diagonal, then that means that this part of the population receives relatively more of the benefit than average. If it is flatter than the diagonal, it means that the corresponding group receives relatively less of the benefit than average. If the Lorenz-curve is parallel to the diagonal, that part of the population gets a proportional share of the benefit.

The Lorenz curve, Gini, and Suits scalars don't work if some benefits have negative values. However, in our analysis, we will have distributions of accessibility expressed in monetary terms taking both positive and negative values. We will employ a remedy for this called polarization (Raffinetti et al., 2015). In the appendix, we show how to compute so-called polarized Gini and Suits indexes. Polarized Lorenz-curve charts are not quadratic, i.e. the diagonal line's inclination is not 45 degrees. However, the scalars and the relative inclinations of the Lorenz-curve versus the diagonal all have the same interpretations.

4. Application and results

In this chapter, we assess horizontal and vertical equity of public

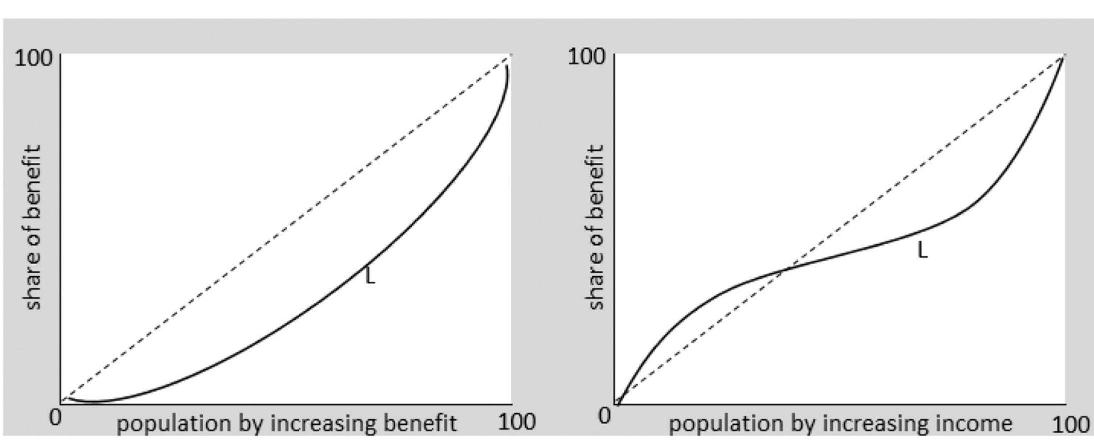

Fig. 2. Lorenz curves used to calculate Gini (left) and Suits (lower) coefficients.

transport accessibility distribution in Stockholm County. We compare this distribution with 1) the accessibility enjoyed by the median resident, and 2) a modeled target accessibility dependent on how densely residents live and how close to the county center (Stockholm Central station) they live. We also assess the equity effects of a proposed policy intervention in operating the commuter trains in Stockholm. As shown in the previous section, we use logsums to measure accessibility and Lorenz curves, Gini, and Suits coefficients to measure horizontal and vertical equity. In Section 4.1, we describe Stockholm and its public transport system. Section 4.2 shows the traditional accessibility equity assessment – studying total accessibility differences). Section 4.3 has our proposed equity assessment– looking at the divergence of actual accessibility from our modeled denseness and centrality dependent accessibility. In Section 4.4, we assess the accessibility effect of the proposed commuter train policy shift.

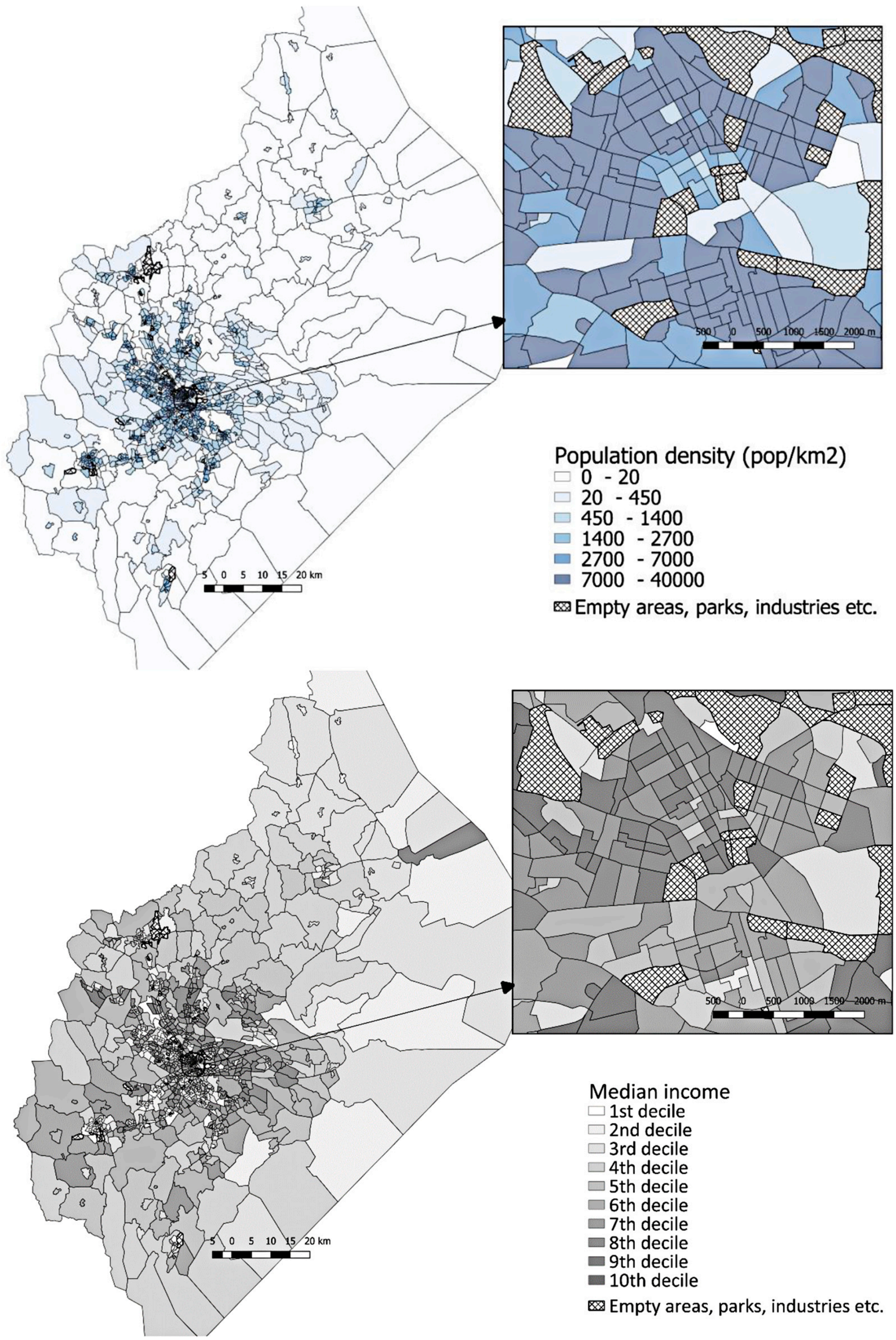

Fig. 3. Population and median income distribution, Stockholm County.

4.1. Stockholm County, population and income characteristics

Stockholm County has a dense core (at some places up to and above 30,000 residents per square kilometer) and large swaths of much more sparsely populated areas. The total population of the county is 2.3 million. The public transport system of Stockholm is comprised of four different modes with 2.9 million boardings on an average winter workday: metro (1.3 million boardings), bus (1.1), commuter train (0.3), and light rail (0.2). In the upper half of Fig. 3, the population density distribution is reported. The coloring is for six groups with the same number of zones in each, as can be seen, five-sixths of the zones have a density below 7000 residents per square kilometer, and a third of the zones have less than 500 residents per square kilometer. Stockholm is known for its long-term monocentric planning with a dominant central core and radial public transport system. The Stockholm County planning authority's current policy is to change this structure by creating sub-centers that will result in a shift toward a polycentric agglomeration. However, Cats et al. (2015) found that such a shift has not yet been realized.

As can be seen from Fig. 3 (lower) and Table 1, the general trend in Stockholm is that high-income dwellers live more densely and closer to the city center. However, a noteworthy break from the trend is the zones with the 10% of the population that have the lowest median income, living rather close to the city center and in dense areas as well.

4.2. Distribution of accessibility

Accessibility is expressed in Fig. 4 (and onwards in this study) as the monetary value derived from subtracting one logsum from another and dividing it with the marginal utility of money, as described in Section 3.1. Here the logsum of the zone where the median resident resides is subtracted from each zones logsum. The currency used is the Swedish "krona" (kr), which is about 0.1 USD or 0.09 Euro. When comparing the actual level of accessibility with the median resident's accessibility, we see that there is a high positive correlation between centrality and accessibility. The green areas are areas with higher accessibility than the median resident enjoys, while red and black areas have lower accessibility.

On the upper right-hand side of Fig. 4, we see the population's distribution with more (positive values) or less (negative values) accessibility than the resident with median accessibility. The distribution yields a Gini coefficient value of 0.65 (bottom left), indicating that accessibility is unevenly distributed. The midpoint of the Lorenz curve is exactly 0.5 since accessibility is defined with the median resident as reference. From the slope of the Lorenz curve, we see that the difference between the 1st and 5th decile is larger than the difference between the 10th and 5th. On the lower right side of Fig. 4, we see that the distribution is regressive as a whole with a Suits value of −0.12. Notwithstanding, it is about proportional for the 20% of the population living in the zones with the lowest median incomes. High-income dwellers (the upper 40%) have higher accessibility per capita than the population as a whole, and the mid-span (2nd to 6th decile) is the part of the population having lower accessibility per capita.

Table 1
The characteristics of the ten income decile zones, each with a population of 174,000 inhabitants.

Income Decile	Average median income (kr)	Land area (km2)	Average distance to central station (km)	Workplaces in areas	Average population density (pop/ km2)
1	146,428	115	14.5	179,534	1503
2	203,182	384	26.0	69,416	452
3	230,016	1251	28.8	75,763	140
4	253,875	1569	23.1	105,108	111
5	276,439	1243	20.1	83,117	139
6	294,278	876	18.0	93,015	198
7	308,573	387	13.0	95,939	451
8	324,103	326	12.3	107,323	535
9	344,545	195	11.6	110,049	884
10	383,761	135	9.2	140,864	1294

4.3. Do residents who live equally dense and close to the center receive the same accessibility?

Given the geographically uneven cost of producing public transport accessibility, we now test the alternative definition of what would constitute a fair distribution of accessibility that we described in the method section. We define the target accessibility by estimating a linear regression model. The dependent variable is the logsum accessibility, and independent variables are the distance from the city center and the home area population density. Table 2 lists the model specifications.

As can be seen from the coefficients levels, the model stipulates that density needs to increase with approximately 2.4 thousand inhabitants per square km to be comparable to being situated 1 km closer to the city center.

In Fig. 5, we see a more haphazard color scheme than in the earlier case, which was agnostic to density and centrality considerations. Also, the difference between the target and the actual accessibility is smaller than the difference between actual accessibility and the accessibility of the median resident. Zones with a surplus of accessibility tend to lie along rail-corridors.

In the histogram presented in Fig. 5 (upper left), the frequency peak around zero surplus/deficit accessibility compared with the target accessibility model is highly concentrated and rather symmetric around zero, which is to be expected given the goodness-of-fit of the regression, function. Even though the values distributed are smaller in this case than the former, the distribution is more uneven with a Gini of 0.8 (lower left). Forty percent of the population has a lower accessibility per capita than the target level, and 60% have a higher accessibility per capita than the target. However, the distribution of differences between actual accessibility and target accessibility is very progressive (lower right); deciles 1–4 are the beneficiaries, while deciles 6–10 are disadvantaged.

4.4. Policy evaluation: Equity distribution effects of introducing skip-stop in the Stockholm commuter train system

Our proposed methodology is not only useful for quantifying the overall distribution of accessibility but can also be applied to assess the distributional effects of specific policy interventions. To demonstrate the latter, we perform an analysis of a recently introduced operations scheme for the commuter trains in Stockholm. During 2018, some of the commuter trains were scheduled to skip some of the intermediate smaller stations. There were two main objectives: (i) to be able to run an operation with high frequency for almost all passengers with the available train fleet and; (ii) to be able to provide those living the furthest from the city center with lower travel times. A secondary motivation, but of interest, was that the "skipped" stations on the northern parts of the system, which are characterized as high-income areas, were areas considered to have higher accessibility than deemed justified. In contrast, the more peripheral areas further north are lower-income areas with lower levels of accessibility. Thus, the test would also be an effort to increase equitable outcomes of public transport operations.

The scheme was launched in December 2017 but was later scrapped due to public protests from the stations skipped. By December 2018, all trains once again stopped at all stations. Fig. 6 shows the Stockholm County commuter train rails with two northbound and two southbound lines from the city center out to the county's outskirts. In the northern part of the system, skip-stop was introduced by changing some existing services to skip-stop while additional skip-stop services would be introduced in the southern part. Red indicates stations with a decreased number of departures, and green indicates stations with an increased

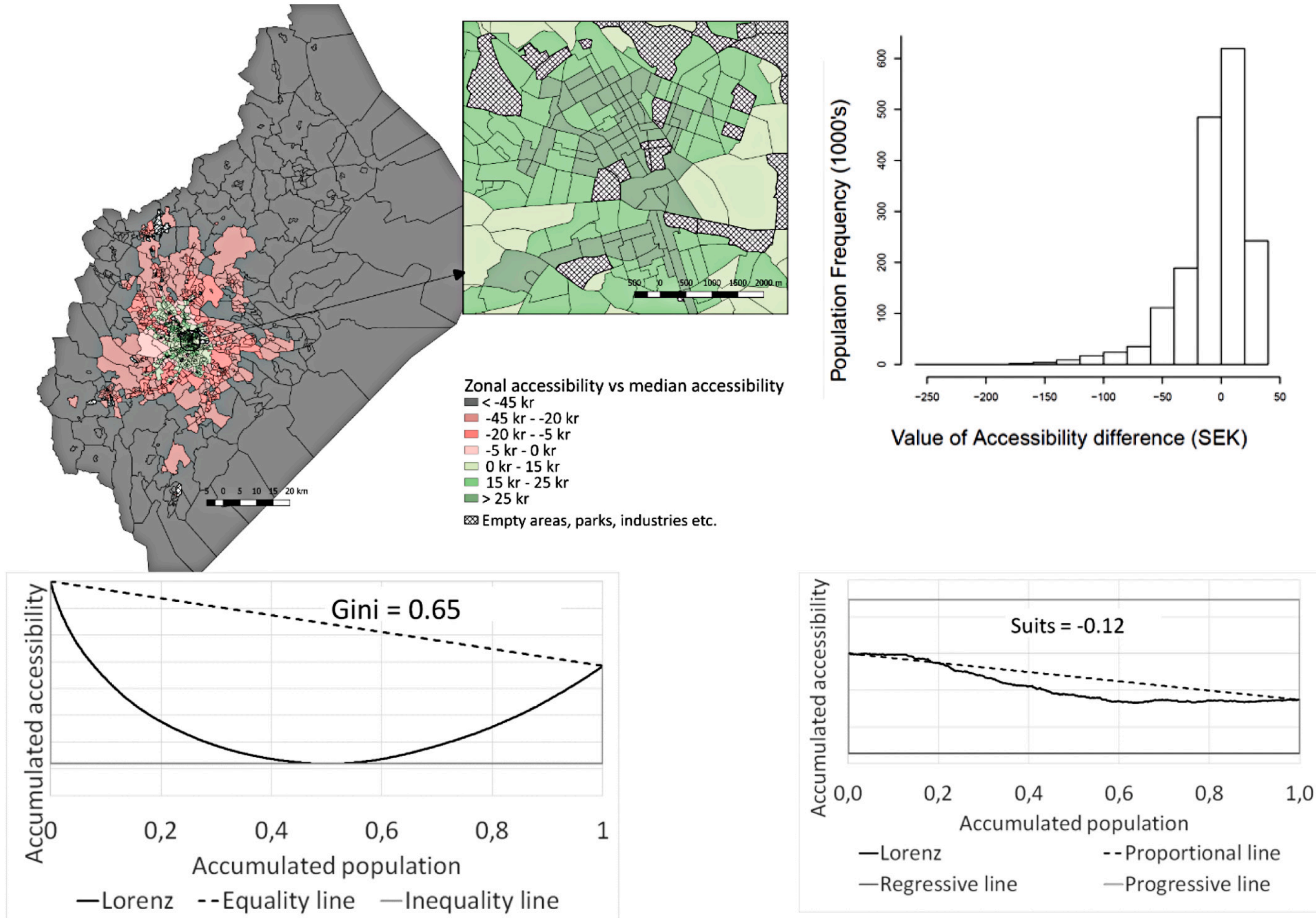

Fig. 4. Distribution of public transport accessibility in Stockholm County.

Table 2
Target accessibility as a regression with distance to the central station and population density as exogenous variables.

	Coefficients	*Stand. Err.*	*t-stat*	*p-value*
Constant	1.1E+01	0.01	782.16	0.00
Population density (pop/km2)	1.3E-05	0.00	9.82	0.00
Distance to central station (km)	−3.2E-02	0.00	−65.01	0.00
Multipel-R	0.90			
R-square	0.81			
Adjusted R-square	0.81			
Standard Err.	0.27			
Observations (N = number of zones)	1364			

number of departures. The coloring of areas shows the accessibility effects of the policy. As can be seen, central parts of the line going from north-west to south-east got decreased accessibility with the skip-stop scheme while the outer parts on the line saw increased accessibility.

Losses and gains are about similarly frequent, as shown in the histogram in Fig. 6 (upper right). As can be expected from a policy implementation that is specific to certain services, it affects a subset of the whole population (lower left). About 20% of the population seeing more substantial decreases or increases in accessibility while the rest of the population sees little to no change. The distributional effects are uneven, with a Gini of 0.92 as it affects travelers very unevenly. The policy, however, seems to be progressive with a Suits of 0.05. The policy impacts appear to be proportional for deciles 1–4, advantage decile five, and disadvantage deciles 6–10.

Putting the policy analysis into our accessibility equity frame, comparing the situation where skip-stop is introduced with the target accessibility, we see a small overall shift where both Gini (with 0.001) and Suits (0.002) increases. These increases indicate a movement from the target but also that the deviation from the target increasingly advantages low-income residents.

5. Conclusions and recommendations

It is prohibitively expensive, and therefore hard to justify, achieving the same public transport accessibility in all areas of a large region. Yet, most studies on equity in public transport accessibility provision do not discern between warranted or unwarranted accessibility differences.

In our study, we set out to define a system goal for public transport regarding accessibility equity where residents living in equally dense and central home areas should receive equal amounts of public transport accessibility. We chose these parameters since they both already are strong predictors for accessibility and because a linkage between land use (density, centrality) and public transport is in line with current trends in planning practices, see e.g., the concept of integrated planning (Hrelja, 2015). We believe such a goal will prove less vague, more implementable, and of higher value to the policy forming process.

We started by studying the distribution of accessibility, finding that it is unevenly distributed over Stockholm County. The accessibility distribution also benefits residents with higher incomes over those with lower incomes. These results are consistent with the literature on accessibility equity (Delbosc and Currie, 2011; Lucas, 2012; Martens, 2016; Banister, 2018). Public transport in Stockholm benefits those living centrally (where house prices are high).

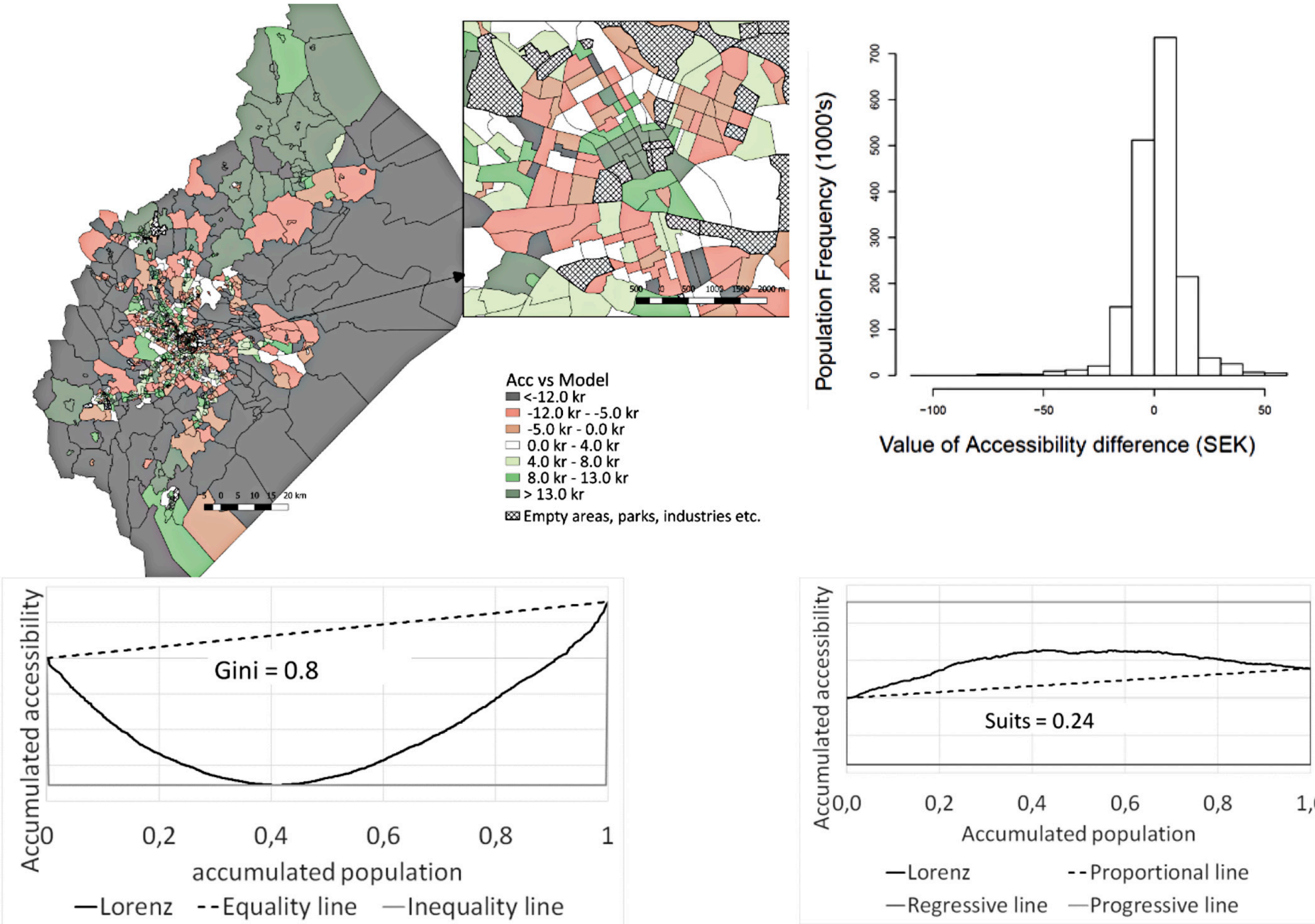

Fig. 5. Surplus and deficit accessibility compared to target accessibility as a function of distance to center and population density.

We then turned to our proposed system goal, choosing to study the distribution of accessibility with the premise that people living in equally dense and equally central areas should receive the same level of accessibility. Assessing the distribution of accessibility against such target accessibility for Stockholm, we find that there still is a somewhat uneven distribution of accessibility. However, this unevenness benefits lower-income residents over higher-income residents – probably because they live peripherally but dense and in proximty to public transport interchanges. Finally, in a policy implementation case, introducing skip-stop services, we find that this policy slightly leads away from the target accessibility while increasing the benefit for low-income residents. This result confirms the hypotheses that the planners at the Stockholm Public Transport Administration had based on their experience and intuition when proposing the system. The implementation was accompanied by strong opposition and was consequently retracted. Presumably, a quantified and detailed material on the policy's distributional impact would have contributed to a more evidence-based debate.

We argue that the proposed methodology is potentially useful for policymakers for the following reasons:

- First, equity of accessibility is easy to measure, but it is hard for the policymaker to decide on the goal for accessibility. The strength of this method is that it provides an achievable goal by establishing a sensible reference.
- Second, with this methodology, two questions can be answered for all proposed policies: will it bring us closer to the goal or farther away from it? And, will it increase or decrease the accessibility for those with lower incomes?
- Third, our proposed methodology incentivizes dense land use even outside the city core (where land use prices might drive more toward urban sprawl) since it will steer public transport provision toward denser areas.

It is, however, important to stress that the method presented in this paper is descriptive rather than normative. Opinions on the ideal distribution from a normative point of view may significantly diverge. Some may argue that those who paid the increased housing cost of living in the city center should have better accessibility. Others may believe that all public transport should gear toward increasing public transport accessibility to those captive riders who do not have transportation alternatives. Our stance is that irrespective of the normative point of view, it is of great value for policymakers to be able to describe distributional effects of policy proposals to have a quantitative decision-support material.

While the methodology and concepts and metrics therein may seem abstract, it is possible to describe the results in terms that can be used in public discourse. Our advice is to communicate which population deciles are impacted by a policy and if the impacts help move toward the target accessibility. We do believe that it is relevant, especially when trying to understand compounded transport disadvantage (Lucas, 2012) to look at groups with the lowest *absolute* accessibility and then refine the analysis by looking at other factors such as social exclusion, low education, and so forth. However, this study's main contribution is in the policy aspect of finding targets and tools for incremental improvement and continuing assessment of transport accessibility provision from an equity point of view. Our proposed measure has the advantages of being economically feasible, concrete, and useful for assessing the

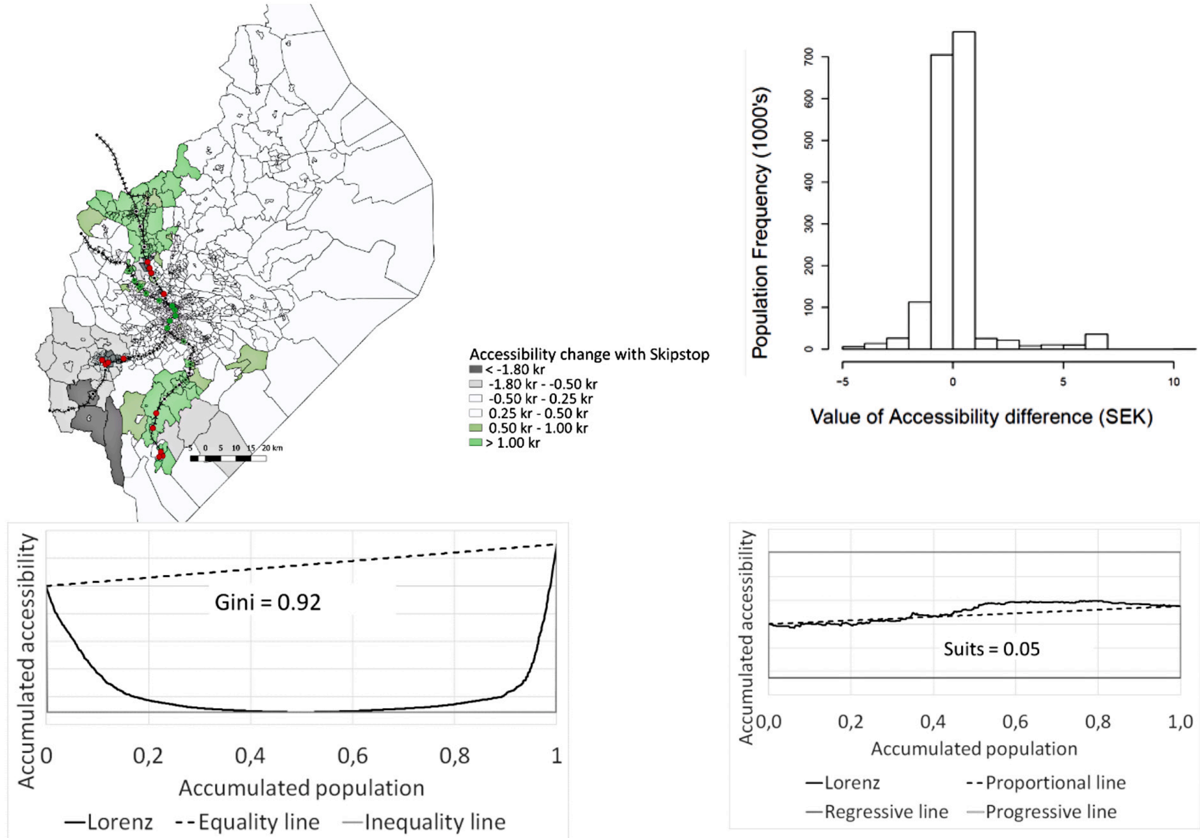

Fig. 6. Change in accessibility when changing to skip-stop on commuter train.

overall situation and looking at individual policy implementations.

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Appendix A. Polarization gini and suits

The Lorenz curve shows the accumulated distribution of some benefit as a function of population share. Gini and Suits are computed scalars from the Lorenz curve. In this study, we use variants of these scalars that can encompass distribution of both positive and negative values since we compare differences between two distributions of accessibility (actual and target) where some areas will have better and some areas will have worse actual accessibility than the target accessibility. Since our measure of accessibility is a monetary one, the sign of the accessibility difference is of importance both practically and pedagogically.

A.1. The Gini coefficient

In Fig. A.1 the Lorenz curve for the regular Gini-calculation is shown in the upper left quadrant. As described in Section 3.3, the y-axis depicts the accumulated share of benefit (g) and the x-axis the accumulated population. The population is ordered by increasing share of benefit. Both axes span the values between 0 and 100 percentage. The Lorenz curve at population share x, L(x), show the share of total benefit g that the x percent of the population with the least g has. So, $L(10) = 5$ would mean that the 10% of population with the least g, together has 5% of all g.

The Gini-coefficient then is the area between the diagonal OB and the Lorenz-curve L, divided by the triangle OAB. The Lorenz curve will always be below or equal to the diagonal OB, and the Gini-coefficient will take values between 0 and 1. In the case of g being perfectly equally distributed (each percentile of the population has 1% of g), the Lorenz-curve will trace the diagonal OB, and the Gini-coefficient will be zero. In the case where one individual receives all of g, i.e., extremely uneven distribution, the Lorenz-curve will trace the line through OAB resulting in a Gini-coefficient of one.

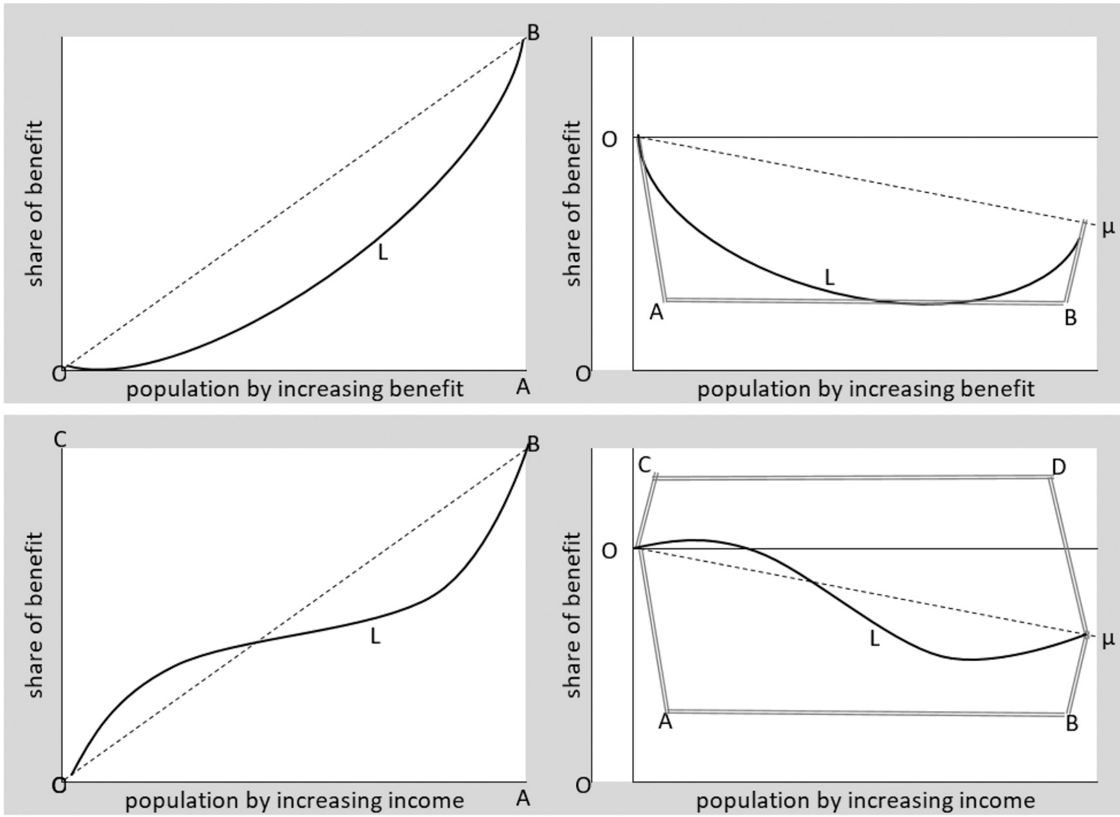

Fig. A.1. Lorenz curves used to calculate Gini (upper) and Suits (lower) coefficients, ordinary (left) and polarization (right) versions.

A.2. The polarization Gini

The above defintions are only permissable when all amounts of g are positive or zero. In case some members of the population receive negative values of g, the characteristics of the Lorenz-curve will yield Gini-coefficients that do not reflect the evenness of the distribution. To expand the use of Gini-coefficients to these type of distributions (Raffinetti et al., 2015) proposed the polarization Gini. The idea is to order the amounts of g in two different buckets, one with the sum of all the negative g's (T^{-}) and one with all the positive g's (T^{+}). Then the most uneven imaginable situation would be that one individual received the sum of all negative benefits (T^{-}) and one received all the positive benefits (T^{+}), and all other individuals receiving zero. This case would make the Lorenz-curve trace the sequence of lines OA-AB-Bμ on the upper right-hand side of A.1. If all members of the population receive the same amount of g, then the Lorenz-curve would trace the dotted line Oμ.

Then the Polarization Gini-Coefficient will be the area defined by the Lorenz-curve and the line Oμ divided by the area within OABμ. As mentioned in Section 3.3, this Polarization Gini and accompanying Lorenz-curve will have the same interpretation as the ordinary Gini and Lorenz curve.

In Table A.1, we present an example with five individuals and four (a-d) different distributions of values and their resulting Gini-coefficients. Case ***a*** is a perfect equity case with all receiving the same amount, while case ***d*** is the most extreme uneven situation with individual 1 having all negative amounts and individual 5 having all positive amounts (resulting in Gini = 1).

Table A.1
Example with five individuals and four (a-d) different distributions of values and their resulting polarization Gin coefficients.

	a	***b***	***c***	***d***
individual 1	−3	−5	−7	−10
individual 2	−3	1	−7	0
individual 3	−3	1	−30	0
individual 4	−3	2	−3	0
individual 5	−3	6	0	5
N	5	5	5	5
T	−15	5	−47	−5
T+	0	10	0	5
T-	−15	−5	−47	−10
μ	−3	1	−9.4	−1
OLμ	0	4.6	3.6	6
OABμ	6	6	18.8	6
Gini coefficient	0.0	0.8	0.2	1.0

A.3. The Suits coefficient

Suits (1977) showed that by ordering the population on the x-axis by increasing income rather than by the amount of g received, one can construct a measure of how income-discriminatory a distribution is, i.e., if the distribution is benefitting low-income members more than high-income members of the population (which is coined as 'progressive' in the context of this paper). The lower left-hand side in Fig. A.1 shows an example of how a Lorenz-curve can look like when the population is ordered as Suits suggests. Note that in this setting the Lorenz-curve can go above the diagonal OB since members of the population can receive high values of g but be ordered to the left due to their low incomes. If K is the area of the triangle OAB, and P is the area under L contained by OAB, then the Suit index can be formulated as:

$$S = \frac{(P - K)}{K} = -1 + \frac{P}{K} \tag{A.1}$$

This formula takes values between −1 and 1. Positive Suits values indicate a progressive distribution of g, while negative values indicate a regressive distribution. In the progressive extreme case, all g is received by the member with the lowest income, making L trace a line through OCB, yielding Suits $= -1 + 2 = 1$. Alternatively, in the extreme regressive case, the member with the highest income receive all g and the Lorenz curve trace the line through OAB with Suits $= -1 + 0 = -1$. When L traces the diagonal OB, P is equal to K and Suits $= -1 + 1 = 0$ which is the proportional case, i.e., the amount of g that a group has is proportional to the groups share of the population and different for different income levels.

A.4. The polarization Suits

The Suits metric is subject to similar problems to those encountered by the Gini coefficient when the g's take both positive and negative values, but we have for this study's purpose developed an original remedy for this. Postulating, analogous with the approach of (Raffinetti et al., 2015), the extreme progressive case, giving the lowest income member T^+ and the highest income member T^-, the Lorenz-curve will trace through points OCDμ on the lower right-hand side of Fig. A.1. The reverse (T^+ to the richest and T^- to the poorest member) will have the Lorenz-curve trace through OABμ instead. However, unlike in the case of the Gini coefficient, in this case, it is not possible to compare the areas in the figure since the two polygons defined by points OCDμ and OABμ respectively are not necessarily the same size. Let A^p indicate the area of the polygon OCDμ and A^r the area of the polygon OABμ. If N is the total population, then the dotted line representing proportionality can be expressed as:

$$Prop(x) = \frac{\mu}{N}\mathrm{x} \tag{A.2}$$

and the line representing the extent to which a distribution is regressive is defined as:

$$Reg(x) = \begin{cases} 0, if\ x = 0 \\ T^- /_N, if\ 1 \le x \le N - 1 \\ \mu, if\ x = N \end{cases} \tag{A.3}$$

Then the area defined by the Lorenz-curve and the lines through OABμ can be formulated as:

$$P = \int_0^N p(x) \tag{A.4}$$

Where p(x) has the following definition:

$$p(x) = \begin{cases} (L(x) - Reg(x)), if\ L(x) < Prop(x) \\ (Prop(x) - Reg(x)) + (L(x) - Prop(x))\frac{A^r}{A^p}, if\ L(x) > Prop(x) \end{cases} \tag{A.5}$$

The Polarization Suits can then be expressed as:

$$S^{pol} = -1 + \frac{P}{K} = -1 + \frac{P}{A^r} \tag{A.6}$$

As with Gini, this definition has the same properties of the original Suits going from extreme regressivity (−1), via proportional (0) to maximal progressivity (1). In Table A.2, we show the Suits of the individuals from Table A.1, imagining that the five individuals would be ordered by income as (5,3,4,2,1) with 5 as the poorest, then the auxiliary statistics N, T^+, T^- and μ would be the same as in Table A.1 and the Ar, Ap, and Suits coefficients would be as follows. Distribution ***a*** is perfectly proportional, ***b*** and ***d*** are progressive (***d*** extremely so), while ***c*** is regressive but close to proportional.

Table A.2
Example of Suits. Using the same example as previous, imagining an increasing income ordering of individuals as (5,3,4,2,1).

	a	**b**	**c**	**d**
Ar	6	6	18.8	6
Ap	6	6	18.8	6
Suits	0.00	0.73	−0.10	1.00

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