The inequality effects of public transport fare: The case of Lisbon's fare reform

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\textbf{A B S T R A C T}

Spatial segregation of social groups within cities and inadequate transport conditions are frequently pointed to as major barriers to improving urban livelihood conditions for disadvantaged groups. For that reason, accessibility measures have increasingly been used as a tool to measure inequality. However, traditional accessibility measures fail to capture both travel costs and individual characteristics, which are central to equity. Therefore, in this paper, we discuss the importance of incorporating fare cost, fare affordability, and individual socio-economic characteristics of transport users into accessibility equity measurements. Given the April 2019 fare policy change introduced in the Lisbon Metropolitan Area (LMA), this study examines how the fare restructuring, the integration of all public transport (PT) modes into a single pass with a maximum cost of 40€ per month, affects inequality levels. Using survey data collected in June and July 2020, we compare the self-reported trip modes and travel costs under Lisbon's previous and current public transport fare systems. We first define 4 benefits associated with the reform and calculate them for all survey respondents. We then used statistical analysis to determine which sociodemographic and locational groups benefited the most from the reform. Finally, using a pseudo-Palma ratio, we compare accessibility inequality levels for income and spatial subgroups before and after the fare price change.

Results show that fare reform had positive effects on commuter accessibility levels, when interpreted as the reduction of generalized costs. Income, age, gender, and transport modal choice were found to be the main characteristics that distinguish the most benefited groups, while other characteristics played a more modest role. These effects, when interpreted from a spatial perspective presented a clear positive association with public transport supply levels. Relative to the impact of the fare reform on equity of benefit distribution, results reinforce that price policies can reduce inequalities.

\section{1. Introduction}

Socio-spatial segregation of cities and inadequate urban transport provision are frequently pointed to as major barriers to improving urban livelihood conditions for disadvantaged groups. Contemporary research on social equity and public transit tends to focus on accessibility and whether disadvantaged populations can access their desired destinations, such as jobs, educational opportunities, and health services. While accessibility is an important component of transport equity, the most frequently used measurement, cumulative opportunities, often ignores the costs associated with transportation, revealing only the number of opportunities accessible within a certain travel time. This produces outputs that can easily be communicated to planners and policymakers, but it oversimplifies the mobility paradigm (Cui and Levinson, 2018; Vale, 2020). By focusing on travel costs and time, in relation to income and public transport (PT) supply, the proposed approach aims to address the limitations of previous studies.

In this paper, we discuss the importance of incorporating fare cost, fare affordability, and individual socio-economic characteristics of transport users into accessibility equity measurements. Fare policy is essential to transport equity because fare costs and structures, such as the availability of passes and the level of fare integration, affect travel decisions such as where to travel, when, by what mode, and even whether to travel at all (Cervero, 1990; Martens, 2012). Transport costs can act as a barrier to access and constrain individuals from reaching their desired destinations. This is especially true for low-income

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households that must spend a larger proportion of their income on transportation than high-income households (El-Geneidy et al., 2016). Similarly, individual characteristics, such as age, income, gender, education level, and car access, influence a person's level of accessibility (Geurs and van Wee, 2004). Failure to take these factors, as well as fare cost, and subsequent (in)affordability, into account leads to a distorted view of both accessibility and equity. Thus, studies that empirically measure the impact of changes in fare prices and structures are needed to better explain equity outcomes.

Accessibility measures have increasingly been used in the transport equity literature, and among these studies monetary costs have gradually received more attention. However, there are few studies that have incorporated transit fares and the individual component into a single study of accessibility and equity, leaving it an under explored area of interest. Most studies have followed two different approaches found in the literature. The first method creates a generalized cost function where the value of time (VOT) is used as an impedance (El-Geneidy et al., 2016; Ford et al., 2015; Ma et al., 2017). Bocarejo and Oviedo (2012) take a similar approach by creating a combined cost function that looks at travel time budget and the percentage of income spent on transportation. Freire et al. (2020), in contrast, uses the generalized cost as a component of utility function, while evaluating the spatial equity resulting from PT supply changes. The second is a cumulative opportunities method that incorporates transport costs as the impedance value (Bittencourt et al., 2021; Büttner et al., 2018; Rodríguez et al., 2017; Vale, 2020). Although these preserve the ease of communication that made cumulative opportunity measurements attractive, they do not reflect equity based on actual transit usage, instead relying on potential accessibility, which does not have a theoretical backing as solid as utility or person-based measurements (Geurs and van Wee, 2004). They also fail to consider any individual components of accessibility. Studies that have attempted to include sociodemographic data to determine their association with accessibility and equity, such as Gkritza et al. (2011), lack detailed demographic information, relying only on average incomes from census data. Most of these studies do not address the necessary spatial detail. They calculate potential equity impacts on accessibility without knowing actual transit usage or real-life out-of-pocket costs, instead considering various cost thresholds based on various single and combined ticket prices (Herszenhut et al., 2022).

Lisbon's fare reduction program offers a rare, real experiment in a transport context where it is more common for public transport fares to increase to keep up with rising costs and inflation. This paper applies both a sociodemographic and spatial analytic approach to measure the equity impact of the fare policy reform implemented in the Metropolitan Area of Lisbon in April 2019. The reform eliminated >300 different daily, weekly, and monthly tickets, with several distinct spatial coverages, into a simple two-option system: municipal and metropolitan travel, each associated with a single ticket price. We address three research questions: (1) what were the benefits of the fare reform; (2) who (individuals and territories) received the most benefit from the fare reform; and (3) what was the impact of the fare reform on equity across the entire metropolitan area as well as within specific territories by looking at the change in inequality levels. We first defined four benefit types and then used exploratory data analysis and statistical inference to determine the populations and territories that saw the most benefit from the fare reform. We then utilized a pseudo-Palma ratio to measure fare equity before and after the reform.

To answer the posed questions, this paper is structured as follows: Section 2 presents a brief overview of the benefits of accessibility, equity in transport research, and fare costs in accessibility measurement. Section 3 is a description of the study context, detailing the changes in the fare system. Section 4 discusses the research design, data, and methods used. Section 5 presents the main results, and finally, Section 6 discusses key findings and concludes with recommendations for future research.

2. Literature overview

Transportation equity encompasses a broad and complex set of relationships between inequalities in transportation and the socioeconomic makeup of a territory. Martens et al. (2019) outline a basic definition of equity, which they describe as the fair distribution of benefits and burdens among members of society. Based on this definition, they distinguish three key components of equity: (1) the benefits and the costs; (2) the populations, or sociodemographic groups, over which the benefits and costs are distributed; and (3) a measurement or principle that determines whether the distribution is “morally proper.” Following Rawls's Theory of Justice (Rawls, 1971), since all individuals have equal moral worth, equity can be understood as the way of conceiving equality by treating disadvantaged groups unequally, but fairly, in order to ameliorate some inequalities. In this vein, Pereira and Karner (2021) suggest that the best way to address issues of transport equity is by prioritizing the needs of underserved or excluded groups.

Social inequalities are manifested in the spatial distribution of benefits and burdens, which can lead to different levels of access to mobility (Ohnmacht et al., 2009). By assuming accessibility is a benefit to be fairly distributed, equity in transportation is related both to the ability to access equal opportunities and to the opportunity to travel itself. Because transport services are not evenly distributed across different spaces, those who are relegated to poorly connected areas may lack access to some opportunities, activities, and services (Social Exclusion Unit, 2003). This poor connectivity, or lack of access to transportation altogether, can deepen the social exclusion experienced by certain populations (Church et al., 2006; Delbosc and Currie, 2012; Hine and Grieço, 2003; Lucas, 2012; Social Exclusion Unit, 2003; Stanley and Lucas, 2008). Women, senior citizens, and low-income individuals are most likely to face these barriers and restrictions, reducing their access and overall mobility. Inadequate transportation options can limit travel choices and the set of available opportunities and activities that some population segments can participate in. Thus, the availability and organization of transportation can affect equity through disparities in the level of accessibility to essential destinations for different sociodemographic groups (Kenyon et al., 2003; Lucas, 2011).

2.1. Accessibility and equity

Accessibility can be defined as the ease of reaching a location (El-Geneidy and Levinson, 2006) by a certain mode, at a certain time (Bhat et al., 2000). Geurs and van Wee (2004) distinguish four basic components of accessibility: land use, transportation, temporal, and individual needs, skills, and opportunities. These characteristics can affect the way the person will travel; for example, whether they have access to a car, whether they have the resources to pay for individual travel or need to travel by active transport or public transport, if their level of education allows them to live close to their place of employment or if they must travel long distances. Lucas (2012) brings a fifth perspective, when referring to the individual ability to interact with the transport system, considering the person's confidence and experience with the transport system and other cultural factors, such as religion, race or gender.

Accessibility is a core concept in studies of transport related social inclusion, equity, and justice. The terms horizontal and vertical equity have been widely discussed in the literature (Bandegani and Akbarzadeh, 2016; El-Geneidy et al., 2016). Horizontal equity refers to spatial justice in the provision of transportation that is balanced and appropriate to the travel needs of all individuals. Vertical equity refers to the level of adaptation of the supply of transportation to the unique needs of certain groups of the population. These groups can be generalized into two categories, people from more disadvantaged and low-income social classes, and secondly, people with special mobility needs, such as the elderly or individuals with disabilities (Riccirardi et al., 2015). An inadequate supply of transportation or a poor distribution of opportunities and services across the city can contribute to social exclusion,
especially of more vulnerable groups. According to Guzman and Oviedo (2018) public transport plays a central role in establishing the accessibility levels of urban populations. However, the high costs of public transport relative to household income end up restricting people’s mobility, pricing them out of all but the essential trips, e.g., work and education.

Accessible public transport systems are paramount to ensuring equal opportunities for all members of a society, since the impacts generated by issues related to mobility system deficiencies, through transportation planning and policies, have a relevant value to citizens. The need to ensure equitable public transport is an essential element of strategies that promote sustainable mobility, as it plays an essential role in shaping opportunities by providing access to jobs, housing, leisure, social and public services (Martens et al., 2012). Lucas (2012) reinforces the importance of incorporating social exclusion metrics into transport planning, stating that the travel needs of the most excluded people will only be met when transportation planning is integrated with accessibility planning and with social policies and programs responsible for housing, health, education, and welfare. When a low-income person does not have access to transportation services for financial reasons, he or she is not accessing opportunities, such as work, education, or health, which could contribute to an increase in income. Thus, they are facing a vicious cycle in which the transportation system is related to the problem of social exclusion.

2.2. Fare COST in accessibility measures

Transport literature has long acknowledged the impact fare cost and affordability have on accessibility. However, this component is often ignored in current research, focusing more on transit network resources and access to opportunities. The implication of this research is that the ability to seize potential opportunities is dependent solely on spatial access to transport infrastructure, with travel time or distance acting as an impedance from reaching the opportunity destination. This system-centric focus disregards the individual, human component of the system, which includes the ability to pay. According to Fan and Huang (2011), transport affordability refers to the financial strain that households experience when acquiring transportation services. Accordingly, transport affordability goes beyond the financial ability to move through space, building a framework that includes sociodemographics and the built environment. Since out-of-pocket costs can limit access to potential opportunities, and regulate those with lower transport budgets to cheaper and slower services, it is regarded as a constraint to making trips and should be integrated into measurement models (Conway and Stewart, 2019).

Current research generally takes one of two approaches when incorporating costs into accessibility measurements; (1) location-based measures that aggregate the monetary costs of travel into a general cost function; and (2) cumulative opportunity measures in which costs and travel times are treated independently and thresholds values of each are used as impedance factors. Works that consider costs by using a generalized cost function either transform time into a monetary value (Guzman et al., 2017; Guzman and Oviedo, 2018; Ma et al., 2017; Ricciardi et al., 2015), or costs into an expression of time (Ford et al., 2015; Oviedo et al., 2019), or both (El-Geneidy et al., 2016). These works measure accessibility by considering only travel time costs and not a user’s ability to pay.

Other studies go a step further by including average incomes, effectively incorporating affordability, or the portion of income spent on transportation, as an impedance factor (Bocarejo et al., 2014; Bocarejo and Oviedo, 2012; Liu and Kwan, 2020; Vale, 2020). Bocarejo and Oviedo (2012) use what they call Real Accessibility, which combines travel time budget and percentage of income spent on transportation as a simple impedance function. Similarly, Liu and Kwan (2020) turn travel time, transit fare and income into a single unit and consider it as a percentage of income (average income for the origin zone taken from travel surveys or census data). Vale’s (2020) Effective Accessibility uses effective speed as an impedance function, which varies as a function of income. Cost is converted to time so that people who must work more hours to afford transport costs travel slower than higher earners. The author used a set value for low, middle, and high-income earners based on census averages. By incorporating user income these approaches generate more accurate results. However, comparing results can be difficult since there is no standard in the literature for calculating the cost of time.

The second approach uses a cumulative opportunity method in which costs and travel times are separate impedance functions (Büttner et al., 2018; Conway and Stewart, 2019; Herszenhut et al., 2022; Rodriguez et al., 2017). Monetary cost limits can be set based on different fuel price or fare cost scenarios. This approach maintains the ease of communication and avoids the possible pitfalls of cost of time calculations, but it does not relate costs to a person’s ability to pay.

3. Case study

The study area of this paper is the Lisbon Metropolitan Area (LMA), an administrative division composed of 18 municipalities. The Metropolitan Area is spread over 3000 km², 3.3% of the total area of Portugal, and is home to approximately 3 million inhabitants, or about 25% of the Portuguese population. It is highly urbanized with around 96% of residents living in “predominantly urban areas.” The Metropolitan Area is split by the Tagus River, with 9 municipalities on the northern bank and 9 on the southern bank. The natural division caused by the river has conditioned the evolution of urban settlements and transport networks. The northern bank, which is centered around the Lisbon municipality, the capital, has greater concentration of development, higher population density, higher socio-economic status, and most public transport services.

Public transport service in the area consists of trains, subways, trams and funiculars, ferries, and buses. The Metropolitan Transports of Lisbon [Transportes Metropolitanos de Lisboa] (TML) is the primary body responsible for planning all intermunicipal and municipal road transport in 15 municipalities. They are also the body responsible for the fare system, implementing the fare policy reform in 2019, which is the focus of this study.

Most literature that incorporates fare costs in accessibility measures is focused on the Global South due to high levels of inequality in relations to accessibility and affordability (Bocarejo et al., 2014; Bocarejo and Oviedo, 2012; Guzman et al., 2017; Guzman and Oviedo, 2018; Herszenhut et al., 2022; Oviedo et al., 2019; Venter, 2016). However, this does not mean that cost is irrelevant in the Global North. This is especially true for Portugal, which has one of the lowest GDPs per capita among all wealthy nations. The national minimum wage was 700 euro/month at the time of our survey, making it the lowest in both terms of absolute amount and in purchasing power among Western European countries. Indeed, of our survey respondents, 24 percent stated they could not pay their monthly transport costs without difficulty before the fare reform, and 15.6% percent of respondents cited cost as a reason for selecting their daily mode of transport. This was the second most selected response, only behind shortest trip time, with 15.9% of respondents. This points to fare costs being a salient issue in the LMA, impacting mobility choices and travel patterns of its residents.

3.1. The reform of the FARE system

Under the old fare system there was a large diversity and quantity of fare types due to each operator offering their own individual tickets and monthly passes. There were also >300 “combined passes,” which were the result of agreements between two or more operators. These are in addition to the ten “intermodal passes” that corresponded to a specific geographic scope in the “zone system” centered around Lisbon, with three rings radiating outwards. This system was limited, only covering a
small portion of the total land area of the LMA and excluding those living in the more remote periphery. Due to the fragmented nature of the old fare system, it was common for public transport users living furthest from the capital, or their place of work, to have to buy multiple passes to reach their destination. This fare system was not only highly complex in its structure and implementation, but also often penalized users living in the periphery whose passes could total >120 euro/month.

On April 1, 2019, a flat fare structure using a single “Lisboa Navegante Pass” was launched, which allows the user to access unlimited public transport trips, on all operators, in the whole of the Lisbon Metropolitan Area for 40 euro/month. Simultaneously, with the entry of the new pass, all other combined passes were removed, resulting in a drastic reduction in the number of existing transport passes and a dramatic simplification of fares. The impact of this change is hard to be overstated. The new pass system not only simplified, but also reduced the cost of public transport for most users. The new faring system offers discounts for senior citizens, students, and those with disabilities, who pay 20 euro/month and for families, who pay a maximum of 80 euro/month for all members of the household.

The overhaul of the faring system was made possible by the implementation of the Program to Support Fare Reduction in Public Transport (PART) [Programa de Apoio à Redução Tarifária nos Transportes Públicos], created by the Ministry Dispatch n.◦1234-A/2019. PART, which is financed by the Environmental Fund, is a national program created to promote public transport tariff reduction and to increase the level of service and expansion of public transport networks. PART’s stated aims are to attract passengers to public transport, while combating the negative externalities associated with mobility, namely social exclusion, greenhouse gas emissions, air pollution, congestion, noise and energy consumption (Diário da República (a), 2019). These objectives are reinforced in the LMA’s Regulation of the General Rules for the Implementation of the Tariff System [Regulamento n.◦ 278-A/2019: Regulamento Metropolitano das Regras Gerais para a Implementação do Sistema Tarifário na Área Metropolitana de Lisboa], which explicitly states that combating social exclusions, promoting the universality and accessibility of public passenger transport services, and promoting economic and social cohesion are objectives of the new, integrated fare (Diário da República (b), 2019).

Despite the policy’s stated aims surrounding social exclusion and equity, no studies thus far have analyzed if the policy has been successful in reaching these aims. This article intends to fill that gap.

4. Material and methods

To answer the posed questions, this paper adopted the steps illustrated in Fig. 1. Details of each step are presented in the subsections of section 4.

4.1. Survey design and data

Primary data used in this study comes from a 2020 survey that served to gather information on daily travel modes and locations, public transport fare purchasing behavior, out-of-pocket costs on transport before and after the fare reform, and demographic information. This survey contained 43 questions and was divided into 6 sections: the first sought to obtain basic mobility data and some details about the most frequent trip the person made, such as travel mode, motivation for selecting the mode, travel time and trip purpose; the second asked specifically about public transport usage; the third had questions about transport expenditures before the fare change; the fourth asked the same questions about transport expenditures after the fare change; the fifth gathered exact origin and travel destination locations; and finally, the sixth obtained basic socioeconomic characterization of the respondent. The survey was open to any adult resident aged 16 and above living in the Lisbon Metropolitan Area and was conducted using LimeSurvey.

Data was collected at the beginning of the Covid-19 pandemic, via a survey disseminated from May 1 to June 30, 2020. Due to the Covid-19 pandemic, it was imperative to adhere to national health safety guidelines, thereby necessitating the exclusion of any in-person surveying. For this reason, the survey was conducted exclusively online, but clearly and repeatedly prompted respondents to recall their travel modes and the corresponding expenses prior to the onset of the pandemic. This precautionary measure was undertaken to ensure the avoidance of introducing any additional unaccounted variables that may confound the
Origins and destinations, incomes, and time calculations are all based on pre-pandemic, February 2020, behavior. Average cost values for car maintenance, fuel, and travel times, used to measure effective speed, were similarly unaffected. Due to the short amount of time that elapsed between the start of the state of emergency and survey collection, we feel confident in the validity of responses. To further confirm the reliability of the data, we verified that it was consistent when compared to Census data (INE, 2022), ensuring we were not at risk of making wrong conclusions in this case. Further, measures were taken to ensure a spatially representative sample, with the percent of respondents from each municipality closely mirroring the percentage of the LMA population that lives in each municipality. Furthermore, both age and gender groups’ proportions were mirrored in the collected data via a continuous monitoring of all collected data. If a discrepancy was observed, the online survey was retargeted to the required audience (whether it was a spatial, age or gender underrepresentation) via social media advertisements and email campaigns. From 1857 responses, >500 were discarded in the process of representation refinement, and only 1302 are used for this paper. Each response had to have a valid 7-digit zip code for the origin and destination and a reported monthly income, which decreased the number of usable responses.

Python and the Pandana library were used to calculate distances between the declared origins and destinations. Pandana is a Python library for network analysis that uses contraction hierarchies to calculate accessibility metrics and shortest paths. When dealing with car trips, travel times were calculated during peak hours of 8-10 am, considering congestion data from January 2020 provided by TomTom (TomTom, 2021). It should be noted that public transport travel times do not consider congestion. For public transport trips, we used the UrbanAccess library, which combines both GTFS (General Transit Feed Specification) and OSM network data in conjunction with Pandana to perform public transport travel-times calculations. Open Street Map (OSM) online map service was used to pinpoint respondents’ residential and job locations, and to calculate urban routes between origins and destinations; and GTFS files provided by the transport authorities of Lisbon (Transportlis, 2021) were used to quantify the spatial distribution of public transport supply across the Lisbon Metropolitan Area. This routing effort returned origin-destination (OD) travel times as result.

We described the sample’s sociodemographic attributes by performing exploratory statistical analysis. The variables of interest included income, age, gender, education level, if they have a driver’s license, and whether they own a bicycle, as well as the total transport expenditures, both before and after the fare reform. This exploration allowed us to spot what variables are correlated with the measured benefits. We did this by checking if there was any difference in the means of these variables for the least and the most benefited groups (lowest and highest terciles, or 33%). Our results (presented in section 5) only reflect the analysis based on the variables that presented statistically significant differences between the two groups. The discarded variables were whether the respondent was a student, had children, were single parents, or if they owned a car, which presented p-values above the determined threshold of 0.05.

To be able to answer the questions posed in section 1 we had to define the benefits to be assessed, which were established through the literature review process. The selected benefits were turned into indicators, calculated for each respondent before and after the fare reform, and related to the dataset. The result was a global view of the impact the fare reform had on all four benefits, and it provided the results necessary to address our first question; to what extent there were any benefits associated with the public transport fare reform.

### 4.2. What are the benefits of the FARE reform?

For this paper we outlined four benefit types that resulted from the fare reform. The first is Absolute Cost Difference (CostDiffabs): this benefit measures the household cost savings of total transport expenditure in absolute terms before and after the fare reform (Eq. 1), which yields a result in euros. \(\text{Total Transport Expenditure} (\text{TrExp})\) was calculated from self-reported monthly expenditure on public transport, including passes, pre-paid tickets, and micro-mobility, and monthly car costs, which includes money spent on gasoline, tolls, and parking. The values used in the calculation were directly reported by respondents for both pre-and post-fare change periods.

\[
\text{CostDiff}_\text{abs} = \text{TrExp}_{af} - \text{TrExp}_{bf} \tag{1}
\]

The second calculated benefit is Relative Cost Difference (CostDiffrel): this benefit measures the household cost savings of total transport expenditure before and after the fare reform relative to household income (Eq. 2), which yields a percentage of household income spent on transport costs. Respondents were asked to indicate their household’s net monthly income (wages, pensions, or allowances). To facilitate accurate reporting, all cost-related questions were designed as open-ended questions, avoiding estimations derived from multiple-choice formats.

\[
\text{CostDiff}_{rel} = \left( \frac{\text{TrExp}_{bf} - \text{TrExp}_{af}}{\text{Income}} \right) \times 100 \tag{2}
\]

The third benefit is the Cost/Time Difference (CostTime): this benefit measures the cost/time savings, where cost/time was determined by dividing the difference in the TrExp before and after (Absolute Cost Difference) by mode-specific travel times. Travel times between the self-reported origins (residence) and destinations (work, school, etc.) were calculated for the given transport mode using the aforementioned process of network analysis performed using the Pandana and urbanaccess libraries, taking into account the transportation infrastructure and service characteristics of the study area (Eq. 3).

\[
\text{CostTime}_{af} = \left( \frac{\text{TrExp}_{bf} - \text{TrExp}_{af}}{\text{TrTime}} \right) \tag{3}
\]

The fourth indicator in our study is the Effective Speed Difference (EffSpeed), (Eq. 4); this benefit measures the changes in effective travel speed where EffSpeed (Eq. 5) is obtained for a given mode and income value by dividing the total distance traveled by a generalized cost measure representing the combined monetary and non-monetary costs associated with using a particular mode of transportation. The concept of Effective speed (Tranter, 2004) considers all the time costs associated with a mode of transportation, rather than just the time spent traveling. The formula for calculating effective speed is speed divided by time, but all time costs are considered in this calculation. E. g., for car drivers, one significant time cost is the time spent working to earn the money needed to pay for all the expenses associated with driving a car. These expenses include annual registration, fuel, parking, tolls, fines, insurance costs, and other taxes associated with owning and operating a vehicle.

\[
\text{EffSpeed}_{af} = \text{EffSpeed}_{bf} - \text{EffSpeed}_{af} \tag{4}
\]

where:

\[
\text{EffSpeed}_{bf} = \frac{\text{atd}}{(\text{ttc} + h_{\text{xtc}} + h_{\text{hct}})} \tag{5}
\]

EffSpeed is the effective speed for mode m, considering an individual with a monthly income inc; atd is the total distance traveled in a month; ttc is the total transport cost associated with atd; h_{\text{xtc}} is the individual’s hourly wage; h_{\text{xtc}} is the number of hours devoted to maintaining the vehicle (cleaning, buying fuel, checking tires, etc.), and h_{\text{hct}} is the total time spent traveling in the vehicle per month. It is worth noting that the Effective Speed indicator is originally presented as an annual estimation in the literature, however, we adapted this temporal scale in our calculations to align with the temporal scale of the other three indicators.

Measuring the changes that resulted from the fare reform using four distinct but related benefits, each slightly more complex than the previous, will give us rigorous results that can inform on the most
appropriate indicators for evaluating the effects of policy interventions in the public transport sector when other conditions remain unchanged.

4.3. Who benefited from the FARE reform?

To address the second research question, we identified which groups benefited most from the public transport fare reform. To achieve this, we compared the sociodemographic characteristics and locations of distinct subgroups within our sample. These subgroups were defined based on the level of benefits calculated for each participant. We divided the respondents into three subgroups per benefit indicator, ensuring an equal number of participants in each tercile. This allowed us to represent the most benefited, mid-level benefited, and least benefited groups, covering the entire sample. To obtain the locational component, we used respondents’ declared residential locations and destinations (as shown in Fig. 2).

The supply level was calculated as the number of unique daily trips provided by all operators (bus, metro, train, ferry) at public transport stops and terminals within a certain range from each respondent’s residence. Catchment areas varied according to the supplied travel mode, assuming 400 m for buses, 600 m for metro, and 800 m for trains and ferries. If the same trip stops at two distinct terminals within the measurement range, the trip is counted only once. Fig. 3 illustrates the spatial groups of lowest, mid-level, and highest levels of public transport supply.

To answer the posed question, we employed hypothesis testing. Our null hypothesis (H0) stated that there is no difference in benefit levels between subgroups, while the alternative hypothesis (H1) proposed that there is a statistically significant difference in benefit levels. Since the groups did not follow a normal distribution, we adopted the Wilcoxon rank-sum test, a non-parametric test, to compare outcomes between two independent samples. For discrete values such as age, income, and PT Supply levels, we used the Mann Whitney U test—as a comparison method. Additionally, we employed the Pearson’s Chi-square test for binary variables like gender, having children, and car ownership. By analyzing the expected results, we can determine if there are any significant differences between the groups in terms of the benefits derived from the public transport fare reform.

4.4. Were benefits of the FARE reform equally distributed?

The third research question focuses on assessing the impact of the fare reform on equity across socioeconomic groups and within specific territories. To measure equity, we adopted an adapted version of the Palma ratio indicator due to its ability to highlight the differences between extreme values (10% richest against the 40% poorest). Typically used to measure income inequalities, we employed the Palma ratio to compare multiple variables while grouping the sample according to either income or public transport supply levels. It is important to note that our results may fall below the equality value of 0.25 due to this adaptation.

To provide a clearer, more numerically intuitive understanding of the results, we calculated a multiplier factor based on the Palma ratio. This factor represents how the average benefit of an individual from the 10% well-off group compares to the average benefit of an individual from the 40% worse-off group. The objective here is to evaluate if there is any indication of reduction or increase in the inequality levels across all the measured benefit indicators (CostDifabs, CostDifrel, CostTimedif, and EffSpeeddif) within the income-based (sociodemographic) subgroups and PT supply-based (locational) subgroups.

While income is a commonly employed metric to assess inequality, it may not capture the full complexity of the impact of the fare reform on different segments of the population. Therefore, we expanded our evaluation beyond income as the sole metric, incorporating an additional measure: public transport supply levels. The inclusion of PT supply levels as a metric is justified by the recognition that access to transportation services plays a crucial role in shaping individuals’ mobility options and opportunities. In the context of Lisbon, it serves as a proxy indicator for accessibility conditions, as there exists a significant correlation between transport supply and access. Areas characterized by high concentrations of job opportunities, educational institutions, and government services tend to exhibit greater transportation options (Costa, 2016). By including PT supply, we could compare the outcomes and assess whether the benefits of the fare change were evenly distributed or if they favored one group over the other. This multi-dimensional approach enables us to explore the interplay between socio-economic factors and spatial considerations, shedding light on potential disparities and providing insights into the effectiveness of the reform in promoting equitable outcomes.

5. Results and discussion

5.1. Sample description

The exploratory analysis aimed to provide a descriptive analysis of the sample’s sociodemographic characteristics, including income, age,
gender, education level, possession of a driver’s license, and vehicle ownership. The sample consists of 56% females and 44% males, which is in line with the reported 54% female/46% male population of the Lisbon Metropolitan Area. The average age of our sample was 42.2 years, which is in proximity to the LMA average age of 43.8 years. Regarding income, the average monthly income in our sample was €1977, surpassing the LMA average of €1439 (INE, 2022). In terms of driver’s license possession, 87% of our sample reported having a driver’s license, while 82% stated that their family owns a car. These proportions were slightly higher compared to the LMA average, where 75% have access to a car (driver’s license rates for the LMA region were not available) (INE, 2017). Additionally, 40% of our sample reported owning a bicycle.

Fig. 3. Areas corresponding to the terciles (33.3, 66.6 and 100 percentiles) of public transport supply level for the respondent’s residential location within the Metropolitan Area of Lisbon.

Fig. 4. Distribution of age and household income.
While there is no official data on bicycle ownership in the LMA due to lack of registry requirements, according to INE (2017), 37% of the LMA population has access to a bicycle. Finally, the educational distribution in our sample revealed that 2% reported having only a basic education, 27% up to high school or trade school, and 71% reported having higher education (see Fig. 4 and Table 1). These figures deviated notably from the LMA averages.

While efforts were made to ensure diversity within the sample, it is important to recognize that it does not precisely mirror the demographic characteristics of the overall population. This is likely a result of snowball sampling that was conducted entirely online and heavily circulated within academic communities. Consequently, the survey naturally precludes individuals who have limited access to online platforms or are less familiar with online survey techniques, namely the oldest segment of the population. However, we would like to highlight that this characteristic of our sample can actually lead to a closer match with the regional population characteristics.

In Portugal, older individuals tend to have lower education levels (OECD, 2021) and are less likely to own a car compared to younger age groups (ACEA, 2023). By not including a large number of older individuals in our survey, our sample composition aligns more closely with the region’s demographics, particularly when considering educational levels and car ownership rates.

Despite inherent limitations associated with sampling, it is worth noting that our sample size was robust and does provide a broad territorial representation, as well as including respondents with varying educational backgrounds, income levels, and possession of a driver’s license and private car. Though disproportionate representation of highly educated individuals poses a limitation and need for caution when interpreting results, we have minimized the impact by comparing aggregated values within subgroups that comprise the extreme values of the sample. By examining these extreme values, we can mitigate the potential impact of the overrepresentation of highly educated individuals on the analysis outcomes. Therefore, while acknowledging this limitation, we argue that our sample still provides a broadly representative picture and can yield valuable insights within the scope of this study.

5.2. Benefits of the FARE reform, global view

Fig. 5 presents both an overlay of the frequency of transport expenditure amounts before and after the fare reform, as well as the distribution of expenditure differences. It is possible to visually identify a higher frequency of 40 euro/month expenditure after, corresponding to the new pass price. While most respondents reported cost savings, this was not universal. As expected, there was an overall decrease in transport expenditures, shown by the left shift along the x-axis. This could indicate that the lower transport pass fare attracted new buyers, but did not necessarily induce a modal shift, so a person maintains their car expenditures while also now purchasing a pass, increasing total expenditure.

Although looking at the change in expenditure in absolute terms is a useful tool, without benchmarking costs to income levels, statements around whether transit costs are high are arbitrary. Since budgets are limited, people must have tradeoffs between transportation and other types of spending. Therefore, the measure of relative costs, or expenditures in relation to income, is a measure of affordability, the most common according to Gómez-Lobo (2011).

Looking at relative cost savings (Fig. 6), the average transport expenditure from our sample decreased from 7.15% of household income to 4.70%. For minimum wage earners, €700/month at the time of the survey, the decrease is even more dramatic. Average transit costs fell from 14.05% to 9.65%. Since the minimum wage has increased to 775€ and the public transport price has been fixed at 40€ until the end of 2023 (Lusa, 2021), the pass now represents 5.1% of the minimum wage.

The CostTime$_{avg}$ benefit introduces the travel time component, which is the most frequently used indicator in traditional accessibility measures. Combining these two factors together allows for richer analysis of the fare reform impact, independent of other sociodemographic characteristics of respondents. As seen in Fig. 7, a decrease in total transport expenditure led to a decrease in the average CostTime$_{avg}$, which fell from 2.74 ratio to 2.02 ratio after the fare reform.

Looking at changes in E/Speed (Fig. 8), the average speed in our sample increased significantly from 3.08 km/h to 10.36 km/h. Analyzing the changes by transport mode, distinct patterns emerge. Public transport users experienced a speed increase of 8.18 km/h (from 3.19 km/h to 11.37 km/h). Similarly, car users experienced an increase speed of 6.45 km/h on average (from 2.92 km/h to 9.37 km/h). Active mode users experienced an effective speed change of 4.7 km/h (from 4.22 km/h to 8.92 km/h).

It is noteworthy that all mode-user groups observed an increase in their E/Speed, indicating that the fare reform had a positive impact across the board. It comes as no surprise that public transport users were the most benefited group, given the substantial increase in their average speed. These findings underscore the positive influence of the fare reform on travel speeds, highlighting the importance of an efficient and accessible public transport system for enhancing mobility outcomes for diverse user groups.

5.3. Benefits of the FARE reform, specific groups

To measure which groups benefited from the fare change, the sociodemographic features of respondents were related to the four benefits we outlined previously. These benefits are our dependent variables in this paper. We then compared the benefit levels between the first and third terciles, the most and least benefited, for all four benefit types and across our interested independent variables. Since preliminary exploration revealed that our sample does not follow a normal distribution and homoscedasticity, a prerequisite for traditional ANOVA or t-testing, we introduced the Mann Whitney U test to test the difference in means between the best off and worse off groups. This was used for discrete values and Pearson’s Chi-square test was used for categorical variables.

The results presented in Table 2 reveal that age, income, level of public transport supply at one’s place of residence, and gender present statistically significant differences in the populations benefiting the most and the least from the fare reform. Moreover, the findings suggest that younger residents, individuals with lower incomes, those residing in
areas with lower PT supply, and respondents that identified as female were more likely to experience advantages from the fare reform, regardless of the chosen benefit indicator. This pattern may arise from the fact that younger residents are likely to have lower incomes than their older counterparts who are more advanced in their careers. Lower earners are also more inclined to rely on public transport, as they may be priced out of using a car for daily travel, even if they reside in areas with limited PT supply. Additionally, our analysis indicates that women derived greater benefits from the fare reform. This observation aligns with other research findings, as women in Portugal earn an average of 11.4% less than men (Eurostat, 2021) and are more likely to utilize public transport, even in households that own cars (Goel et al., 2022).

The results further support previous studies highlighting the disproportional impact of transport fares on women.

Our findings indicate a positive relationship between higher PT supply at the destination and the extent of benefits received in terms of CostDif_{abs}, CostDif_{rel} and CostTime_{dif}. This observation is likely attributed to the concentration of job opportunities in the central areas of Lisbon, which are well-served by public transport and less car-friendly in terms of lower speeds and higher parking fees compared to peripheral locations.

Regarding the possession of a driver's license, it was found to be a significant factor for all benefits except CostDif_{abs}. For the other three benefits, the highest benefitting tercile had a lower likelihood of having
a driver's license. This variable was more telling than car ownership, which was only significant for the CostDifrel benefit.

Looking at education levels, we found that individuals with higher education were less likely to benefit from the fare reform, although, this finding held significance only for CostTimeRel. One possible explanation is that educational attainment is positively correlated with income, allowing this subgroup to afford private transportation more easily. It could also be that they self-select to live in more isolated high-end communities that are further from public transport.

These nuanced factors suggest a complex interplay between public transport supply, driver's license possession, education levels, age, gender, and the specific benefits obtained from the fare reform.

### 5.4. Impact of FARE reform on equity levels

To assess inequality levels, we applied the Palma ratio in a bivariate manner, i.e., we aggregated the comparison subgroups according to one variable (income or public transport supply levels) and calculated the

### Table 2

Summary of hypothesis test results, comparing the four previously outlined benefits for the highest tercile (t1) and lowest tercile (t3), and the sample sociodemographic characteristics.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>BENEFIT TYPE</th>
<th>CostDifftot</th>
<th>CostDifrel</th>
<th>CostTimeDiff</th>
<th>ElSpeed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>t1</td>
<td>t3</td>
<td>P Value</td>
<td>t1</td>
<td>t3</td>
</tr>
<tr>
<td>Income (€/month)</td>
<td>0.032*</td>
<td>&lt; .001*</td>
<td>0.007*</td>
<td>0.006*</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>1819.96</td>
<td>2056.16</td>
<td>1645.09</td>
<td>2124.13</td>
<td>1835.83</td>
</tr>
<tr>
<td>Age</td>
<td>0.02*</td>
<td>&lt; .001*</td>
<td>0.003*</td>
<td>0.002*</td>
<td>0.146*</td>
</tr>
<tr>
<td>Mean</td>
<td>38.65</td>
<td>41.12</td>
<td>38.76</td>
<td>41.52</td>
<td>38.44</td>
</tr>
<tr>
<td>PT Supply</td>
<td>&lt; .001*</td>
<td>&lt; .001*</td>
<td>&lt; .001*</td>
<td>&lt; .001*</td>
<td></td>
</tr>
<tr>
<td>Origin (mean)</td>
<td>526</td>
<td>763</td>
<td>543</td>
<td>730</td>
<td>532</td>
</tr>
<tr>
<td>PT Supply</td>
<td>&lt; .001*</td>
<td>&lt; .001*</td>
<td>&lt; .001*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Destination (mean)</td>
<td>1171</td>
<td>1002</td>
<td>1173</td>
<td>871</td>
<td>1227</td>
</tr>
<tr>
<td>Gender</td>
<td>0.026*</td>
<td>0.028*</td>
<td>0.043*</td>
<td>0.014*</td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>172</td>
<td>204</td>
<td>169</td>
<td>200</td>
<td>171</td>
</tr>
<tr>
<td>Female</td>
<td>261</td>
<td>228</td>
<td>264</td>
<td>231</td>
<td>263</td>
</tr>
<tr>
<td>Education</td>
<td>0.203*</td>
<td>0.059*</td>
<td>0.013*</td>
<td>0.518*</td>
<td></td>
</tr>
<tr>
<td>Basic Edu</td>
<td>10</td>
<td>9</td>
<td>13</td>
<td>7</td>
<td>11</td>
</tr>
<tr>
<td>Higher Edu</td>
<td>128</td>
<td>105</td>
<td>141</td>
<td>116</td>
<td>133</td>
</tr>
<tr>
<td>Driver's License</td>
<td>0.148*</td>
<td>0.007*</td>
<td>0.011*</td>
<td>0.003*</td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>364</td>
<td>378</td>
<td>358</td>
<td>384</td>
<td>354</td>
</tr>
<tr>
<td>No</td>
<td>69</td>
<td>54</td>
<td>75</td>
<td>47</td>
<td>80</td>
</tr>
<tr>
<td>Owns Bicycle</td>
<td>0.427*</td>
<td>0.083*</td>
<td>0.225*</td>
<td>0.111*</td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>162</td>
<td>173</td>
<td>154</td>
<td>178</td>
<td>159</td>
</tr>
<tr>
<td>No</td>
<td>271</td>
<td>259</td>
<td>279</td>
<td>253</td>
<td>275</td>
</tr>
<tr>
<td>Public Transport Mode</td>
<td>&lt;.001*</td>
<td>&lt;.001*</td>
<td>&lt;.001*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Public Transport</td>
<td>371</td>
<td>47</td>
<td>375</td>
<td>180</td>
<td>411</td>
</tr>
<tr>
<td>Car</td>
<td>50</td>
<td>200</td>
<td>49</td>
<td>227</td>
<td>20</td>
</tr>
<tr>
<td>Active</td>
<td>12</td>
<td>47</td>
<td>9</td>
<td>24</td>
<td>3</td>
</tr>
</tbody>
</table>

Income and age values are presented as means. The boldface denotes P < 0.05. *Mann Whitney U test.

Palma ratio based on income groups for the four benefits indicators.

### Table 3

<table>
<thead>
<tr>
<th>INCOME GROUP</th>
<th>10%High (£) (n = 129)</th>
<th>40%Low (£) (n = 516)</th>
<th>10%High Average</th>
<th>40%Low Average</th>
<th>Palma Ratio</th>
<th>Low to high multiplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Income</td>
<td>601,220</td>
<td>515,024</td>
<td>14660</td>
<td>998</td>
<td>1.167</td>
<td>4.67</td>
</tr>
<tr>
<td>ptSupply Origin</td>
<td>113,072</td>
<td>342,296</td>
<td>876 trips/day</td>
<td>663 trips/day</td>
<td>0.330</td>
<td>1.32</td>
</tr>
<tr>
<td>Total Transport Expenditures</td>
<td>13,296</td>
<td>49,022</td>
<td>103,07</td>
<td>695,00</td>
<td>0.271</td>
<td>1.08</td>
</tr>
<tr>
<td>TotTransExp Before</td>
<td>11,264</td>
<td>31,327</td>
<td>127,31</td>
<td>660,71</td>
<td>0.360</td>
<td>1.44</td>
</tr>
<tr>
<td>Difference (af-bf)</td>
<td>-2031</td>
<td>-17,695</td>
<td>-15,16</td>
<td>-34,29</td>
<td>Result: Inequality increased</td>
<td></td>
</tr>
<tr>
<td>Variations</td>
<td>-15.3%</td>
<td>-36.1%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relative Transport Expenditures</td>
<td>303</td>
<td>5365</td>
<td>2.35%</td>
<td>10.39%</td>
<td>0.056</td>
<td>0.23</td>
</tr>
<tr>
<td>TotTransExp Before</td>
<td>261</td>
<td>3492</td>
<td>2.02%</td>
<td>6.76%</td>
<td>0.075</td>
<td>0.30</td>
</tr>
<tr>
<td>Difference (af-bf)</td>
<td>-42.29</td>
<td>-1873</td>
<td>-0.33%</td>
<td>-3.63%</td>
<td>Result: Inequality reduced</td>
<td></td>
</tr>
<tr>
<td>Variations</td>
<td>-14.0%</td>
<td>-34.9%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transport cost / Travel time</td>
<td>228</td>
<td>1277</td>
<td>1.77€/min</td>
<td>2.47€/min</td>
<td>0.179</td>
<td>0.71</td>
</tr>
<tr>
<td>Cost/Time After</td>
<td>191</td>
<td>805</td>
<td>1.48€/min</td>
<td>1.56€/min</td>
<td>0.238</td>
<td>0.95</td>
</tr>
<tr>
<td>Difference (af-bf)</td>
<td>37</td>
<td>473</td>
<td>-0.29€/min</td>
<td>-0.91€/mi</td>
<td>Result: Inequality reduced</td>
<td></td>
</tr>
<tr>
<td>Variations</td>
<td>16.2%</td>
<td>37.0%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Effective Speed</td>
<td>646</td>
<td>1164</td>
<td>5.00 km/h</td>
<td>2.25 km/h</td>
<td>0.555</td>
<td>2.22</td>
</tr>
<tr>
<td>EffSpeedAvg Before</td>
<td>1568</td>
<td>4703</td>
<td>12.15 km/h</td>
<td>9.11 km/h</td>
<td>0.333</td>
<td>1.33</td>
</tr>
<tr>
<td>Difference (af-bf)</td>
<td>922</td>
<td>5359</td>
<td>7.15 km/h</td>
<td>6.86 km/h</td>
<td>Result: Inequality reduced</td>
<td></td>
</tr>
<tr>
<td>Variations</td>
<td>142.7%</td>
<td>304.2%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

PalmaRatio = 10%high / 40%low | low to high multiplier = 10%high Average / 40%low Average.
Palma Ratio to another associated variable (each of the four benefits). The Palma ratio tells us how much the 10% most well-off subgroup benefits when compared to the 40% worst-off subgroup. A result of 0.25 means equality. If the result is >0.25 this indicates that more benefits went to the 10% high subgroup, while a result of <0.25 indicates that more benefits went to the 40% low subgroup. For the sake of clarity, results were also expressed in terms of a multiplier representing how many times the average benefit of a member of the 40% low group fits in the average benefit of a 10% high group member. For instance, a multiplier of 1.5 for Total Transport Expenditure would mean that, on average, a member of the 10% most well-off subgroup has 50% higher average benefit of a member of the 40% low group fits in the average benefit of a 10% high group member. For instance, a multiplier of 1.5 for Total Transport Expenditure would mean that, on average, a member of the 10% most well-off subgroup has 50% higher average benefit of a member of the 40% low group fits in the average benefit of a 10% high group member. For instance, a multiplier of 1.5 for Total Transport Expenditure would mean that, on average, a member of the 10% most well-off subgroup has 50% higher average benefit of a member of the 40% low group fits in the average benefit of a 10% high group member.

Inequality results for income groups show that income inequalities are high within our sample population. The high-income subgroup earns, on average, 5 times more than the low-income group. However, PT supply levels between income groups are not as unequal, with the high group having about 30% more PT supply than the low group.

Looking at each benefit, results varied. We found that inequality in Total Transport Expenditures increased even though the low-income subgroup had a higher absolute cost reduction. Both groups lowered their total expenditure, but the Palma Ratio increased from 0.271 to 0.360, meaning that more benefit went to the high earning group. The Relative Transport Expenditure benefit presented a slight reduction in inequality. Still, after the fare reform the average transport costs relative to income is >3 times higher for the 40% low-income subgroup. The Cost of Travel Time benefit presented a substantial inequality reduction, with the “after” Palma Ratio close to equality (0.238). The inequality reduction of both the Relative Transport Expenditures and Cost/time strengthen the idea that an increase in Total Transport Expenditures inequality can have a positive impact on the reduction of other inequalities.

Effective speed presented an inequality reduction. However, the 10% high subgroup experienced higher speed gains (7.15 km/h against 8.68 km/h), in absolute terms. Despite gains in 3 benefit types, the 40% low-income group still spends more of their income on transportation, has a higher Cost/time ratio, and travels slower than the high-income group.

Inequality results for locational subgroups, as defined by PT supply at origin, indicate that there is very high inequality in access to transport. The high group has 10 times the PT supply when compared to the 40% low group. The high access to transport group also has higher monthly incomes, but this is not as pronounced, as their incomes are on average 1.23 times higher than a low access group member. We found that inequalities fell when looking at the Total Transport Expenditure and Relative Transport Expenditure benefits, albeit modestly, as there were no relevant differences between the two subgroups’ income levels. It should be noted that those living in the worst- served areas spend 1.5 times more on transport when compared to the well-served group (85.94€ v. 57.12€). The Cost of Travel Time benefit presented a substantial reduction in inequality levels.

Both subgroups benefited in terms of their Effectivespeed, which translates into less time wasted in supporting transportation. However, the inequality levels that benefited the 10% high subgroup before the reform suffered a reversion. After the fare reform, the 40% low access subgroup experienced a greater increase in their Effectivespeed, becoming the most favored subgroup. Inequality intensity remains unchanged.

6. Conclusions

This study investigated the effects of a transport fare reform that occurred in the Lisbon Metropolitan Area in 2019. It looked at the levels and the fair distribution of commuters’ transportation benefits and was able to answer the three questions posed in the introduction. Simply put, the fare reform had positive effects on commuter accessibility levels, when interpreted as the reduction of generalized costs. Income, age, gender, and transport modal choice were found to be the main characteristics that distinguish the most benefited groups, while other characteristics played a more modest role. These effects when interpreted from a spatial perspective presented a clear association with public transport supply levels. In the end, our results show that the overall effects of the fare reform contributed to a more equitable distribution of benefits.

In relation to what were the benefits of the fare reform (1st research question), four main conclusions were reached. First, the savings on absolute transportation expenses is the most directly observable measure. However, it does not consider modal choices (speeds), locations (travel distances) and income. Second, the benefit of reducing the commuting budget per month, if adopted, allows for an interpretation of the savings in transport expenses weighted by income. Nonetheless, it

Table 4

<table>
<thead>
<tr>
<th>PT SUPPLY GROUP</th>
<th>10%High (%)</th>
<th>40%Low (%)</th>
<th>10%High Average</th>
<th>40%Low Average</th>
<th>Palma Ratio</th>
<th>Low to high multiplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Income</td>
<td>301,888</td>
<td>979,358</td>
<td>€2340</td>
<td>€1897</td>
<td>0.308</td>
<td>1.23</td>
</tr>
<tr>
<td>pSupply Origin</td>
<td>246,796</td>
<td>95,206</td>
<td>1913 trips</td>
<td>184 trips</td>
<td>2.592</td>
<td>10.37</td>
</tr>
<tr>
<td>Total Transport Expenditure</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TotTransExp Before</td>
<td>9064</td>
<td>69,915</td>
<td>€70.26</td>
<td>€135.49</td>
<td>0.166</td>
<td>0.66</td>
</tr>
<tr>
<td>TotTransExp After</td>
<td>7369</td>
<td>44,549</td>
<td>€57.12</td>
<td>€85.94</td>
<td>0.164</td>
<td>0.66</td>
</tr>
<tr>
<td>Difference (af-bf)</td>
<td>-1695</td>
<td>-25,566</td>
<td>€13.14</td>
<td>€49.55</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Variations</td>
<td>-18.7%</td>
<td>-36.6%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relative Transport Expenditures</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RelTransExp Before</td>
<td>563</td>
<td>4711</td>
<td>4.36%</td>
<td>9.13%</td>
<td>0.120</td>
<td>0.48</td>
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<tr>
<td>RelTransExp After</td>
<td>472</td>
<td>2881</td>
<td>3.66%</td>
<td>5.58%</td>
<td>0.164</td>
<td>0.66</td>
</tr>
<tr>
<td>Difference (af-bf)</td>
<td>-91</td>
<td>-1830</td>
<td>-0.70%</td>
<td>-3.55%</td>
<td></td>
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<tr>
<td>Variations</td>
<td>-16.2%</td>
<td>-38.8%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transport cost / Travel time</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost/Time Before</td>
<td>240</td>
<td>1472</td>
<td>1.86/€/min</td>
<td>2.85/€/min</td>
<td>0.163</td>
<td>0.65</td>
</tr>
<tr>
<td>Cost/Time After</td>
<td>187</td>
<td>872</td>
<td>1.45/€/min</td>
<td>1.69/€/min</td>
<td>0.215</td>
<td>0.86</td>
</tr>
<tr>
<td>Difference (af-bf)</td>
<td>-53</td>
<td>-600</td>
<td>-0.41/€/min</td>
<td>-1.16/€/min</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Variations</td>
<td>22.0%</td>
<td>40.8%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Effective Speed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EffSpeedAvg Before</td>
<td>463</td>
<td>1602</td>
<td>3.59 km/h</td>
<td>3.10 km/h</td>
<td>0.289</td>
<td>1.15</td>
</tr>
<tr>
<td>EffSpeedAvg After</td>
<td>1255</td>
<td>5695</td>
<td>9.72 km/h</td>
<td>11.03 km/h</td>
<td>0.220</td>
<td>0.88</td>
</tr>
<tr>
<td>Difference (af-bf)</td>
<td>792</td>
<td>4092</td>
<td>6.14 km/h</td>
<td>7.93 km/h</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Variations</td>
<td>-171.0%</td>
<td>-255.4%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

PalmaRatio = 10%high / 40%low | low to high multiplier = 10%high Average / 40%low Average.
still disregards distances and speeds. Third, the travel cost/time indicator incorporates both distances and speeds but disregards the commuter’s income. Fourth, the effective speed indicator incorporates all these factors, although being more complex and abstract, which hinders its understanding.

Regarding whom received the most benefit (2nd research question), each adopted indicator gives us a slightly different picture. Groups defined by income, gender, and modal choices presented statistically significant differences for all four adopted indicators. These three criteria are tied together as income is strongly associated with modal choice (Jann-Díaz and Videla, 1989; Johansson et al., 2006) and gender (Dollar and Gatti, 1999). The relevance of other sociodemographic groups was less universal, presenting mixed results. It is worth mentioning that characteristics of transport mode availability (bicycle ownership and driver’s license) are relevant to the effective speed indicator (which is heavily affected by the transport modes life-time costs), and education, normally associated with income, related to changes in the cost of travel time and the relative difference of transportation expenses.

Results also show that benefits affect certain locations more than others. However, this perception applies only to locations defined by the PT supply levels. The fare reform affected only prices and did not affect the PT supply, which means that all variables other than prices are controlled. The location-based groups presented significant differences in benefits, with a clear advantage to well served areas. Fare price policies face a clear limitation imposed by the spatial dimension of city planning. In terms of accessibility, this realization stresses the distinction between the land-use and transport components of accessibility, expressed by Geurs and van Wee (2004).

Relative to the impact of the fare reform on equity of benefit distribution, results reinforce that price policies are capable of reducing inequities. For all four indicators, in most cases, inequity decreased apart from Absolute Differences in Transport Expenditures for Income groups. In this case, both groups’ expenditures decreased (if compared to the period before the reform), however, the poorest 40% group (who before the reform already had lower expenditure than the 10% wealthier group, on average) experienced a higher reduction in their average transport expenditure. In terms of equality this may be undesirable, but from an equity point of view, this seems to be a good sign. The other exception was the effective speed differences for localized groups (based on areas of distinct PT supply levels). The inequality levels did not present a clear reduction; however, they were inverted. Before the reform the wealthier group presented higher average effective speed, while, after the reform the poorest group’s effective speed took the lead. This condition raises important questions: if the least benefited group in terms of one indicator (e.g., PT supply) becomes the most benefited group in another indicator (e.g., Effective speed), how can we interpret equity levels? What are (or should be) the effects on transport policy and social justice? To this end, there is a need to continue to identify more meaningful and comprehensive equity indicators.

Declaration of competing interest
None.

Data availability
Survey responses contain sensitive information and will not be shared. Other data, such as GTFS data and OpenStreetMap data, are publicly available.

References