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Examining circuitry of urban transit networks from an equity perspective

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ABSTRACT

Circuitry of transit networks, defined as the ratio of network to Euclidean distance traveled from origin to destination stop, has been known to influence travel behavior. In addition to the longer time spent in travel, for networks where fare is based on distance traveled, higher circuitry also means higher fare for the same Euclidean distance. This makes circuitry relevant from an equity perspective. Using a case study of the urban transit network of Amsterdam in the Netherlands, this study explores the role of transit circuitry on the disparity in distance traveled by travelers' income profile and its implications on travel times and costs for networks with distance-based fares. The analysis is based on travel patterns from smart card data for bus, tram, and metro modes, combined with neighborhood level income data. Results reveal that in Amsterdam, the higher the share of high income people living in proximity to a transit stop, the lower the circuitry of journeys from the stop, when controlled for the Euclidean distance covered and spatial auto-correlation. The uneven distribution of circuitry exacerbates the disparity in distance traveled, and hence fare paid between the income groups. However, the travel time per Euclidean distance favors the low income group, possibly due to the circuitous routes serving these areas being compensated by higher travel speeds. This study highlights the role of transit network design in determining its equity outcomes and emphasizes the importance of considering equity during route and fare planning. The process followed can be adapted to examine equity for other urban networks.

1. Introduction

Transit networks are often optimized to maximize directness and minimize transfers (Zhao and Ubaka, 2004) while minimizing costs and travel times. Circuitry¹ is defined as the ratio of the network and Euclidean distances between an origin-destination (OD) pair (Barthélemy, 2011), and is a popular measure to quantify the directness of road and transit networks. Circuitry of transit networks has been found to influence travel behavior at various decision-making levels. Lee et al. (2015) studied five Korean cities and found evidence of a strong relationship between circuitry and transit ridership. At a long-term decision level, Levinson and El-Geneidy (2009) found in their study of twenty US cities that people tend to locate themselves in areas with smaller circuitry for home-work trips – with the circuitry of used routes being smaller than randomly selected routes in the network. At a short-term level, Huang

and Levinson (2015) found that circuitry can explain the mode choice of commuters in Minneapolis-St. Paul, Minnesota – a low transit mode share was found to be associated with higher circuitry. Transit circuitry was also found to explain transit route/path choice in some studies (Kim et al., 2019; Raveau et al., 2014). Such a direct relationship with travel demand makes circuitry an important transit performance measure.

In the case of transit routes that follow the road network, circuitry is a function of the street network layout. In addition to the circuitry of individual transit lines, service network structure and transfer locations also impact the circuitry of journeys experienced by passengers. For example, radial networks are expected to have a higher circuitry for journeys between two suburbs that require transferring in the core compared to tangential or ring networks that may provide a direct connection. Sometimes transit agencies intentionally design routes with high circuitry to maximize coverage, even though it may discourage

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¹ Circuitry is similar to the road 'detour factor' as introduced by Cole and King (1968). However, in transit literature, Circuitry is a more prevalent term. Hence we have used the term 'Circuitry' in this paper.

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ridership on those routes (Huang and Levinson, 2015).

It is common for transit networks to be designed based on efficiency and demand, without explicitly focusing on the equity aspect (Soltani and Ivaki, 2011). Such a design may end up favoring a particular section of the population (high income) over others. This is particularly true for mono-centric European cities where low-income residents typically live away from the city center in areas with lower population density, leading to more circuitous routes. Transit routes with higher circuitry imply a longer (network) distance traveled for the same Euclidean distance covered. The impact of this on passengers is two-fold. Firstly, longer network distance results in longer travel times for passengers, all else being equal. Secondly, for transit networks where the fare is calculated based on network distance traveled (such as in Amsterdam, and Beijing metro), circuitry directly impacts the fare paid by travelers. Essentially, travelers using highly circuitous routes end up paying more for a worse-off connection. Hence, in such networks, an uneven distribution of circuitry can result in an uneven distribution of both travel times and fare paid per Euclidean distance covered. Both aspects make circuitry relevant from an equity perspective. However, to the authors' knowledge, there is limited research on the distribution of circuitry observed within a transit network, and its impact on travelers from different population groups.

This study investigates the role of transit circuitry on the disparity in distance traveled, and its implications in terms of travel times and costs for three income levels. This is done by undertaking an empirical assessment of circuitry for the urban transit network of Amsterdam using a combination of anonymized smart card data (which contains automatic fare collection (AFC) data), and automatic vehicle location (AVL) data. Based on the information on circuitry for all transit journeys made within the network (by metro, tram, and bus), the study addresses the following questions for the case study system:

- Do travelers from lower income areas have more circuitous transit journeys?
- What is the contribution of circuitry to the distribution of distance traveled by different income demographics?
- What implications does this have on the travel times and fare paid by them?

2. Literature review

Transport equity is a complex topic with multiple definitions and interpretations. For this study, one of the commonly used definition in transportation studies, the 'fairness in distribution of impacts', is adopted (Litman, 2002). Martens et al. (2019) highlight three key components of a transport equity analysis: defining what impacts (burdens or benefits) are considered, which population or social groups are they distributed over, and what constitutes as being fair. The literature so far has included a wide range of impacts associated with transport provision: road and transit network supply (Ahmed et al., 2008; Delbosc and Currie, 2011), environment and health externalities (Feitelson, 2002), travel costs, taxes and subsidies (El-Geneidy et al., 2016; Eliasson and Mattsson, 2006; Pucher, 1981), and access to jobs and other opportunities (Guzman et al., 2017; Neutens et al., 2010). Further, there are a range of groups emphasized in equity analyses, including but not limited to genders, income classes, and spatially, mentally or physically disabled groups. Litman (2002) classifies equity in two types - horizontal and vertical. Horizontal equity refers to fairness between individuals of the same ability, income and social class. Vertical equity includes fairness between individuals across different abilities, income and social classes.

Accessibility has been one of the most common impacts (benefit) of transport that is subject to a transport equity analysis. This is because any change in policy or intervention has an impact on accessibility, both short and long term. While most of the research on accessibility focuses on travel times or distances, travel cost has also been recognized as an

important barrier to transport access (Foth et al., 2013; Kaplan et al., 2014; Pritchard et al., 2019). Hence, it is typically included in equity evaluations, either exclusively (El-Geneidy et al., 2016), or along with other factors (Currie, 2004).

Several studies (Bandegani and Akbarzadeh, 2016; Brown, 2018; Farber et al., 2014; Rubensson et al., 2020) have investigated how fare is distributed across population groups, and evaluated the impact of alternate fare policies on equity. In Utah, Farber et al. (2014) found that lower socio-economic groups tend to travel shorter distances with high ridership – making distance-based fare policy more vertically equitable than zonal fares. Similarly, in Toronto, Foth et al. (2013) found that residents in lower socio-economic areas had shorter travel times due to proximity to city center. In contrast, Rubensson et al. (2020) noted that for Stockholm, lower income travelers made a higher proportion of longer journeys, for which distance-based fare was vertically inequitable. As highlighted by them, the equity outcome of a fare policy is dependent on the geographical distribution of income levels, land-use and travel patterns.

In many European cities, the city center typically has better access to amenities, which increases land value in close proximity to it. This results in a decline in income with increasing distance from the center (Brueckner et al., 1999). With this pattern of income distribution, low income residents need to travel longer (Euclidian) distances to reach the city center, where most opportunities are located. In addition, the disparity in (network) distance traveled could be either alleviated or exacerbated by differences in circuitry of transit routes serving different areas. The variation in distance traveled is expected to be a combination of these two effects.

Fig. 1 shows the relationship between the land-use patterns, transit network design and the outcomes of fare paid and travel times observed in the network. The socio-demographic characteristics of a person impact the need for travel. Observed travel behavior in the network is a function of both land-use and transport network. Examining the factors separately can help to provide tailored solutions for addressing each of these issues based on their respective contributions. However, the literature to date has primarily focused on the contribution of land-use patterns to distance traveled, and not enough attention has been given to the contribution of transit network design. Our study aims to address this gap by examining the contribution of circuitry in the distribution of distance traveled and in turn the fare paid and travel times.

A key question underlying all equity analysis is how fairness is defined. Carleton and Porter (2018) emphasize that most transport equity studies measure the level of equality. To move from equality to equity, it is paramount to define what is considered fair, for which several, often conflicting theories of justice exist. Pereira et al. (2017) provide a detailed review of these theories in the context of transport. We start by measuring the levels of equality in the current distribution of circuitry in the network, and its contribution to the (in)equality of distance traveled in the network. We specifically focus on measuring vertical equity by investigating whether the distribution favors an income group. Next, by the means of Gini index, horizontal equity of distribution of circuitry in the network is analyzed. However, we refrain from giving absolute judgements on equity, with respect to suggesting appropriate corrections for mitigating inequity concerns, which will depend on the specific theory of justice chosen to be followed.

3. Method

3.1. Transit circuitry

Transit circuitry of a (passenger) journey is calculated as the ratio between the network distance traveled and the Euclidean distance between the origin and destination of the journey. A journey may or may not include transfer(s) within or across transit modes. A route is defined as the combination of transit lines and transfer stops used by a passenger in his/her journey. Mathematically, it can be expressed as,

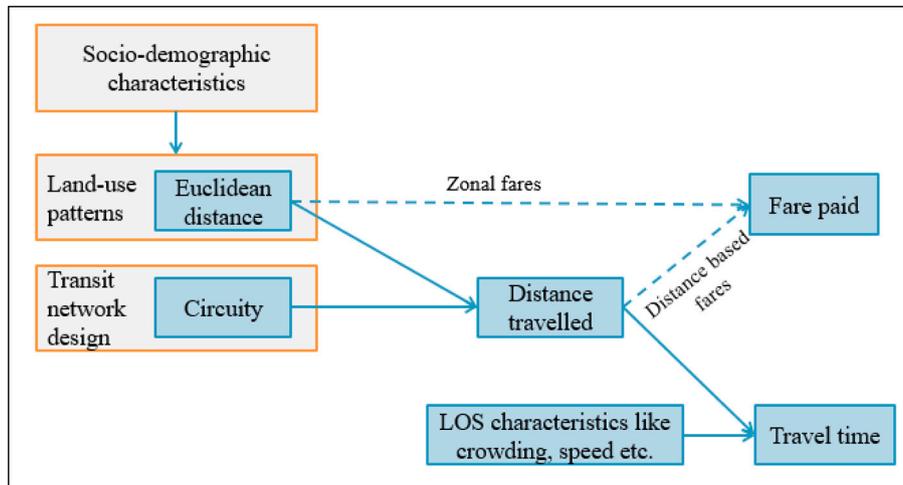


Fig. 1. Relationship between circuitry of a network, travel times and fare paid.

$$C_{o,d,r} = \frac{\sum_{l=1}^{L_{o,d,r}} x_l^r + \sum_{l=1}^{L-1} x_{l,l+1}^r}{x_{o,d}^e} \forall o, d, r \quad (1)$$

where, $C_{o,d,r}$ is the circuitry for a journey between origin-destination transit stops o, d using route r ; x_l^r the network distance traveled on leg l of route r between o, d ; $x_{l,l+1}^r$ the transfer distance between leg l and $l+1$ of route r between o, d ; $x_{o,d}^e$ the Euclidean distance between o, d ; and $L_{o,d,r}$ the number of legs in the journey between o, d using route r .

Fig. 2 shows a schematic representation of it.

The term 'realized transit circuitry' is used to indicate the circuitry that is obtained based on the actual routes used by the journeys made in the network (as opposed to potential ones based on shortest path between an O-D pair). The information on journeys made in the network is obtained from smart card data. The subsequent sections first describe the case study network, followed by how the smart card data is processed to obtain the realized transit circuitry, and how it is linked to the income data to facilitate an equity analysis.

3.2. Introduction to case study network and data sources

The analysis is performed for the urban transit network of Amsterdam (Fig. 3), and includes all bus, metro and tram lines operated by GVB, the transit network operator of Amsterdam. The time period for analysis is spring 2018 (28th May–1st July). During this time, 41 bus

lines, 15 tram lines and 4 metro lines were operational. The city center of Amsterdam is served by a dense network of tram lines, mainly connecting the center with large residential areas. The metro provides connections between the south-eastern suburbs and the city center, and a ring line to the west of the city. The bus completes the network, mainly to and from the northern part of the city, as feeder links to the metro, and some tangential and some radial services where tram and metro services are missing.

This study uses a combination of anonymized smart card data and automatic vehicle location (AVL) data to obtain information on the routes used for all transit journeys made in the network. The Dutch smart card (called OV-chipkaart) records information on both check-in and check-out for all modes (for more information see van Oort et al. (2015a)). For the urban transit network of Amsterdam, it provides approximately 675,000 transactions per day on average for the study period. The AVL data is publicly available for all transit modes in the Netherlands (see van Oort et al. (2015b) for more details).

The smart card data used in this study does not provide any information on the socio-demographic characteristics of the traveler or the type of fare paid. Hence, we use the income data from Central Bureau of Statistics (CBS) Netherlands (2020a), where this information is available at a neighborhood level (with 470 neighborhoods in Amsterdam). Two relative income indicators per neighborhood have been used for this study: the share of persons belonging to the top 20% or the bottom 40% of the national personal income distribution (Bresters, 2019).

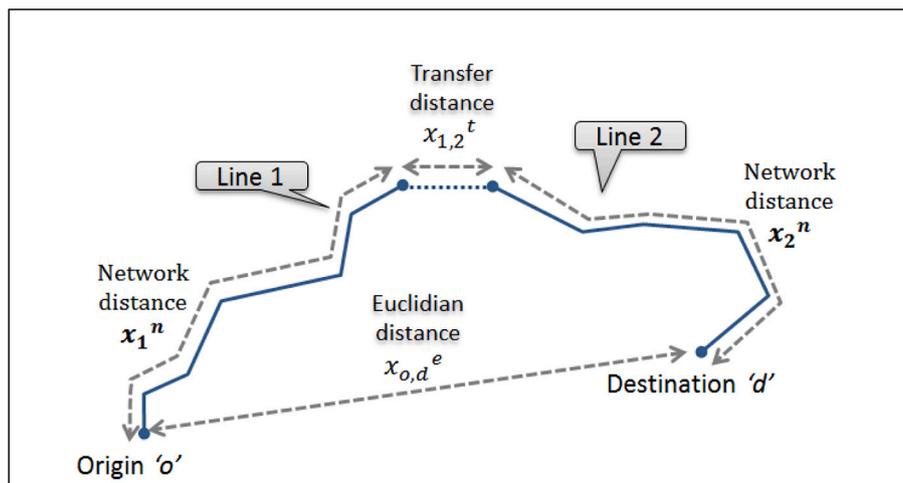


Fig. 2. Schematic representation of circuitry measurement for a two-leg transit journey.

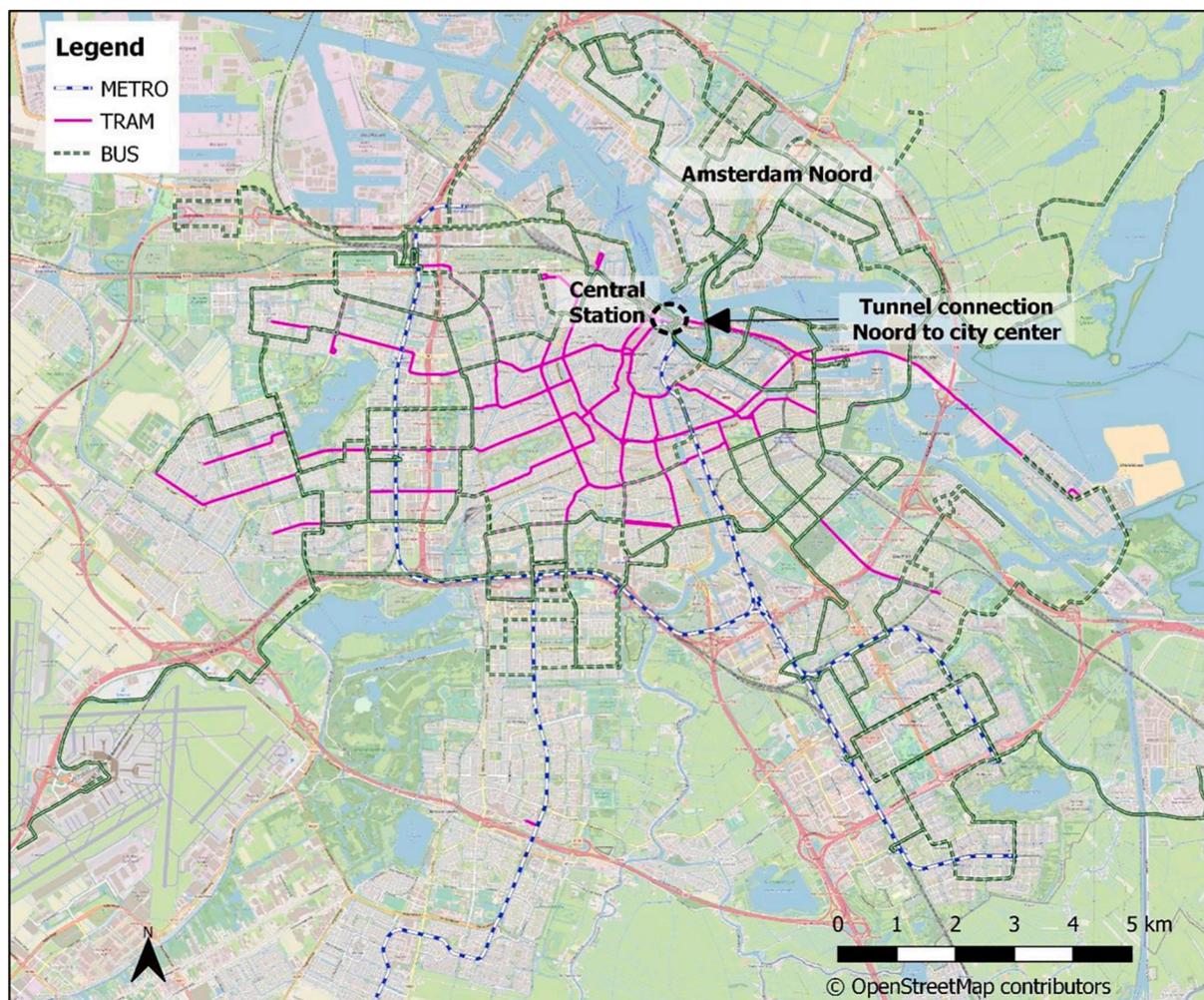


Fig. 3. Urban transit network in Amsterdam.

3.3. Data processing steps

The first step in data processing is to convert raw (anonymized) smartcard transactions to linked trips (or passenger journeys). This process is described as below:

1. Data cleaning: The smart card and AVL data were first cleaned to remove incomplete, invalid or unrealistic records (~3.3%).
2. Destination Inference: This was carried out for records with missing check-outs (4.2% in the data) using the method detailed in Zhao et al. (2007).
3. Assigning journey length: For buses and trams in Amsterdam, the check-in and check-out happen inside the vehicle, and the information of the transit line used is recorded in the smart card data. Based on the origin, destination and transit line used, the network distance traveled is added for each bus and tram trip. For metro, the check-in and check-out happen at the station entrance/exit, and the information on transit line(s) used is not directly available from the smart card data. For the purpose of this research, the network distance corresponding to the shortest path is used for these trips.
4. Transfer inference: Individual smartcard transactions (trips) are matched with the corresponding AVL data to identify transfers using existing algorithms (for more details see Dixit et al. (2019)). For each journey, the network distance and transfer distance for each leg of the journey is recorded.

After processing the data and accounting for transfer inference, over

500,000 journeys per day were obtained. Once the origin, destination and route are known, circuitry of each journey is calculated as the ratio of the sum of traveled (network) distance and transfer distance, and the Euclidean distance between the origin and destination stops of the journey, as expressed in Eq. (1). Journey level circuitry values are then aggregated by mode(s) used, distance traveled and origin transit stop by taking an average across all journeys.

Some journeys in the network might include unnecessary detours which are made by choice. Such detours are more likely to happen for leisure trips than for commute trips. Restricting the time period to the weekday morning peak period is expected to minimize the proportion of leisure trips. In addition, only origin-destination and route pairs with a minimum of 20 journeys over the study period have been considered, to ensure only reasonable routes are included. With this threshold, we retain 87% of the journeys made in the network.

3.4. Linking income with travel data

To study the relationship between income and circuitry, the next step is to link the neighborhood level income data to the observed circuitry data from smart card. Since the residential location is not directly available from the smart card data, it is assumed that the travelers reside in the catchment area of the transit stop from which they start their transit journey during the weekday morning peak period. Accordingly, the income characteristics of the catchment area of the transit stop have been used as a proxy for income profiles of the travelers using the transit stop during the morning peak period. An (area) weighted average of all

neighborhoods within the catchment area (400 m radius) of a transit stop has been used for this. For this reason, only the journeys starting in the morning peak period (7 AM to 10 AM) on weekdays are considered for this study, which constitute approximately 16% of the total journeys in the processed data.

Fig. 4 shows the resulting spatial distribution of the share of low-income persons by transit stop. The areas in the north, and south-east and west peripheries of the city have a higher than average share of low-income residents. The city center of Amsterdam has a relatively lower concentration of low-income residents. However, unlike the typical pattern of a European mono-centric city, some higher-income areas are also located further away from the city center in southern and eastern peripheries of the city.

3.5. Equity analysis

Once the income profile is assigned to each transit stop, the distribution of Euclidean distance, circuitry and network distance by income is analyzed to identify patterns. Next, a multiple regression is conducted to disentangle the impact of income on circuitry, while controlling for the Euclidean distance covered in the journey. First, an Ordinary Least Squares (OLS) regression was conducted, and the residual errors were tested for spatial autocorrelation. For defining neighbors, a distance based weights matrix with inverse distance weighting was used. After testing different options of distance, a threshold of 600 m was identified as providing the best results. Using the resulting weights matrix, Moran's I statistic was applied to detect the presence of spatial autocorrelation in the data. On identifying the presence of spatial autocorrelation, the Lagrange Multiplier (LM) tests were conducted to identify the appropriate spatial model. Based on the test results, Spatial

Error Model (SEM) was chosen for this analysis. For more details on spatial autocorrelation and spatial models, the readers are referred to Anselin (1988) and LeSage (2008).

Finally, the equity of fare paid and travel times is evaluated using Gini coefficient (Gini, 1912). Gini coefficient quantifies the horizontal (in)equity of an outcome (an equity indicator such as accessibility), and has been a popular measure for horizontal equity analysis in transport (Delbosch and Currie, 2011; Rubensson et al., 2020). It varies between 0 and 1, with 0 signifying perfect equality, and 1 the perfect inequality where the entire outcome is concentrated with one individual.

4. Results

4.1. Transit circuitry in Amsterdam

The majority of transit trips in Amsterdam in the morning peak have a circuitry of 1.4 or lower (Fig. 5), with an average circuitry of 1.28 for the entire network. A large share of trips (38%) in the study period are made exclusively by metro, where the network distance between subsequent stops is close to the Euclidean distance, resulting in circuitry values close to 1 for shorter distances. Large circuitry values also occur for metro (for longer distances) which makes the average circuitry value for metro as 1.21. The circuitry of bus trips is found to be 1.54, which is the highest amongst the three modes. A reason for this is that they typically run in low density areas of the city which often have indirect routes to maximize coverage. Trams on the other hand have a dense network in the city center with relatively less detours (average circuitry of 1.18).

Fig. 6 shows the spatial distribution of circuitry, measured as the average circuitry of all transit trips originating from a certain stop. The size of the bubbles indicates the relative number of trips originating

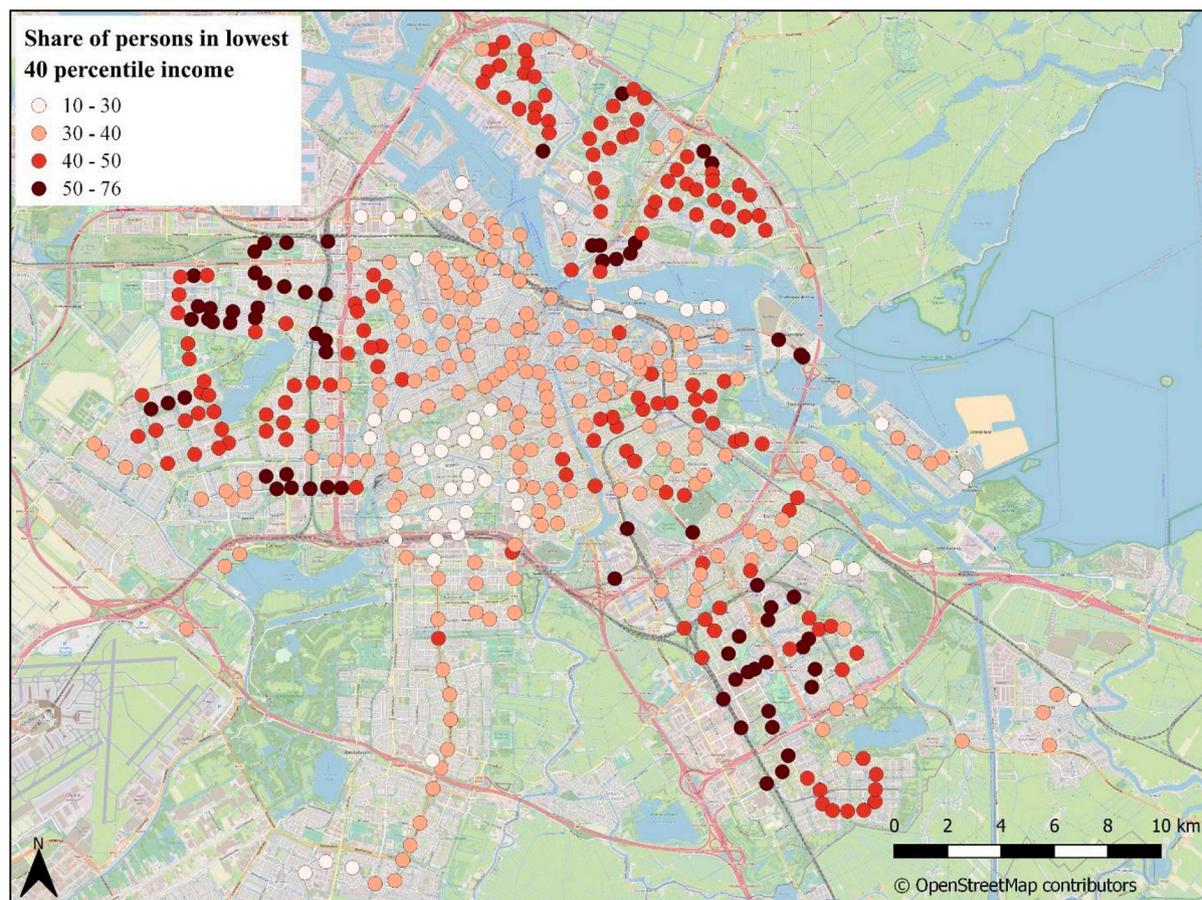
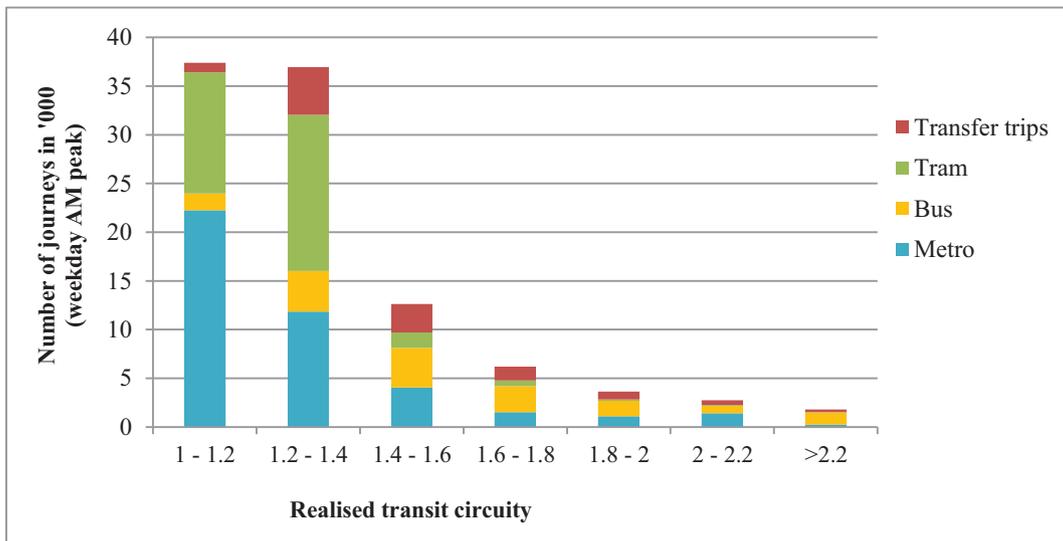


Fig. 4. Share of people in the bottom 40% of the national personal income distribution.



Note: Circuity for metro includes metro-to-metro transfers

Fig. 5. Realized transit circuitry in Amsterdam. Note: Circuity for metro includes metro-to-metro transfers.

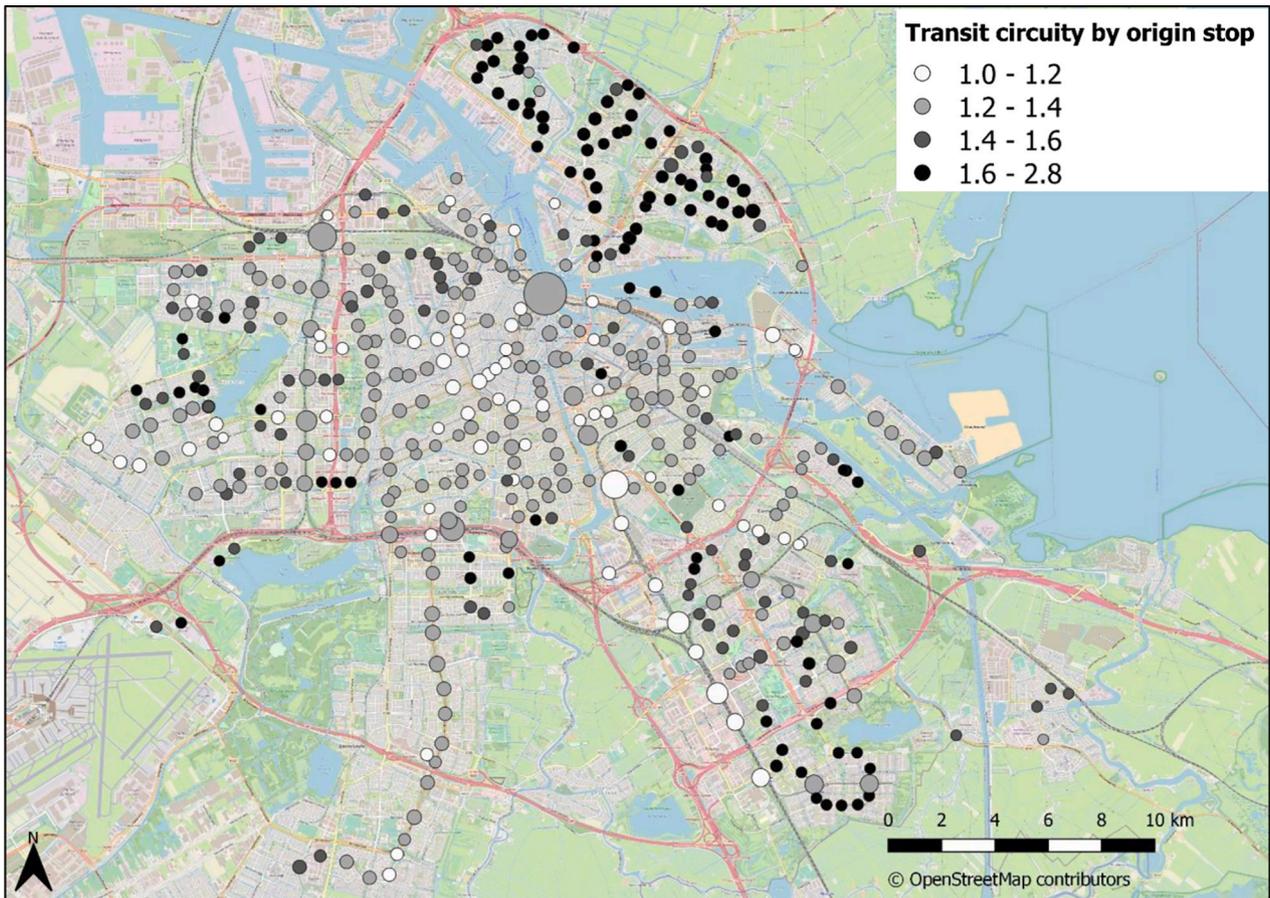


Fig. 6. Spatial distribution of transit circuitry in Amsterdam by origin transit stop.

from the respective stop. The areas to the north of the river (known as Amsterdam Noord) show distinctly higher values of circuitry, with the majority of stops having a circuitry of 1.6 and above. This is expected as the only transit connection from the Noord to the city center in the study period was via buses that used a single tunnel to cross the river (Fig. 3). In addition to Noord, all higher circuitry stops are found in the peripheral

areas of the city, whereas most stops in the city center have an average circuitry of 1.4 or lower. However, it is worth noting that many of the peripheral areas of the city also have a low circuitry, for example those in the south-east parts of the city, due to the presence of direct metro and tram lines.

The realized circuitry increases marginally with Euclidean distance

traveled for journeys without transfers, especially for metro and tram (Fig. 7). On the other hand, it decreases with increasing Euclidean distance for journeys with transfers. The circuitry for tram journeys is largely unaffected by journey length. As expected, metro journeys have the lowest circuitry for shorter distances. The steep increase in circuitry after 3 km and the drop around 8 km could be due to the circumferential nature of the metro lines in the (relatively small) network. In line with Fig. 5, bus is found to be the most circuitous of the modes (including transfer trips), regardless of the distance covered, with an overall increasing trend for longer distances. Most of these larger distances traveled are to and from Amsterdam Noord. The trends for bus and metro modes are in contrast with those reported by Huang and Levinson (2015) for Minneapolis–St. Paul region, where circuitry was found to decrease with increasing Euclidean distance. As discussed, this contrast could be attributed to the geometry of metro and bus routes in Amsterdam.

As discussed earlier, we measure the ‘realized’ instead of ‘potential’ circuitry in this study. However, this could lead to a selection bias. For example, a traveler could have chosen a route with sub-optimal circuitry due to other desirable characteristics such as lower travel times or less crowding. We further investigate this by comparing the observed circuitry values with the shortest-path circuitry for each observation in our data. The results show that for 96% of journeys, the difference between circuitry of observed routes and the shortest path circuitry is less than 0.01 units. This means that the observed circuitry distribution is close to the potential circuitry distribution in our case, and we therefore conclude that our data contains minimal selection bias.

4.2. Circuitry, income and distance traveled

Next, the relationship between the income, circuitry and distance traveled is explored. As described in Section 3.4, transit journeys have been assigned the income profile of their origin transit stops. For this analysis, the transit stops have been divided into three categories based on their share of low income residents, roughly corresponding to the mean ± standard deviation in the study area:

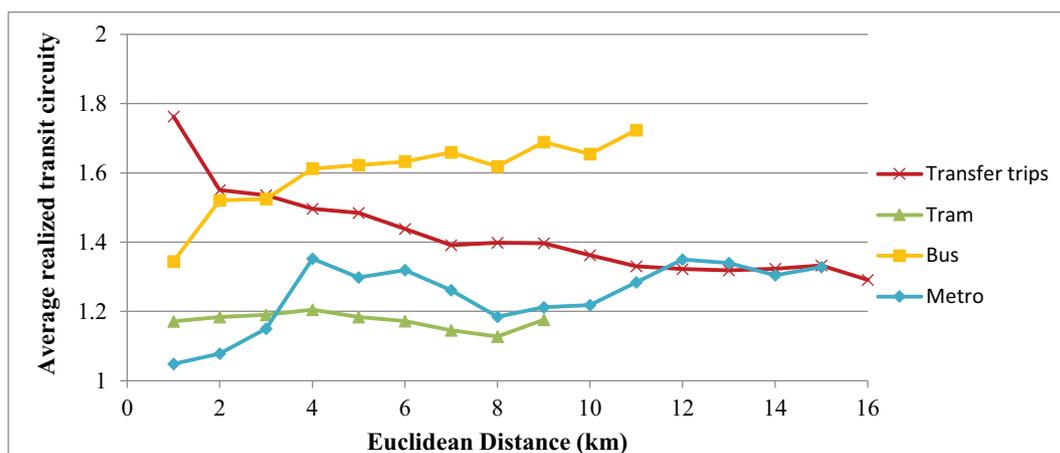
- Group 1 with a share of low-income residents of less than 30%
- Group 2 with a share of low-income residents between 30 and 50%
- Group 3 with a share of low-income residents of more than 50%

We first establish how far the travelers from each of these three groups travel by transit, as measured by the Euclidean distance of their journeys (Fig. 8). This gives an indication of the proximity of travelers to various opportunities they need to access. It is noted that travelers from

predominantly low-income areas (group 3) have a much higher proportion (52%) of longer journeys (>4 km) compared to the rest of the travelers, for whom this proportion is only ~34%. The results support the amenity-based theory (Brueckner et al., 1999) that higher income persons locate themselves in places with greater proximity to amenities, with travelers from Group 3 traveling longer Euclidean distances (median distance of 4.1 km), compared to the rest (median distance between 2.8 and 3 km). The difference in distribution between areas of low to medium share of low-income people (group 1 and 2) is less pronounced.

If the circuitry is the same across all journeys made in the network, the distribution of network distance will follow the distribution of Euclidean distance. However, the uneven distribution of circuitry could either reduce or exacerbate the differences in journey length distribution in the network. To investigate this, we plot next the circuitry distribution for the three income groups (Fig. 9). Circuitry is found to have the highest median value (1.24) for predominantly low-income areas (group 3). However, the spread of circuitry distribution is also found to be the widest for this income group, with 25% travelers having circuitry values of less than 1.05 – the lowest between the three groups. The least amount of detours are experienced by travelers from Group 2 with a median circuitry value of 1.19 for this group. Even though the distribution of Euclidean distance is comparable for group 1 and 2, the relatively favorable circuitry distribution of group 2 is expected to reduce the network distance traveled by this group. Concurrently, the higher circuitry values for low-income areas may worsen the disparity in distance traveled for this group compared to the rest of the population.

Arguably, people with higher income are likely to locate themselves in areas with higher proximity to opportunities due to which they need to travel shorter (Euclidean) distances (Fig. 8). In addition, these areas may also be served by a denser transit network with direct routes to most destinations, because of which they benefit from smaller detours, leading to lower circuitry values. To isolate the relation between high-income areas and circuitry, a regression analysis is conducted with Euclidean distance as a control variable to represent the proximity to opportunities for different income groups. The analysis is carried out on data aggregated for each origin stop with the natural logarithm of average circuitry as the dependent variable and share of high-income residents as one of the independent variables. Additionally, all stops in Amsterdam Noord have systematically higher circuitry values (Fig. 6). To control for these differences due to the structure of the city, a dummy variable for transit stops located in Amsterdam Noord is added. First an OLS regression was undertaken and based on the tests for spatial autocorrelation as described in section 3.5, a Spatial Error Model was implemented to incorporate the spatial dependence in the data. Table 1 shows the results of the Spatial Error model.



Note: Circuitry for metro includes metro-to-metro transfers

Fig. 7. Circuitry by Euclidean distance covered and mode used. Note: Circuitry for metro includes metro-to-metro transfers.

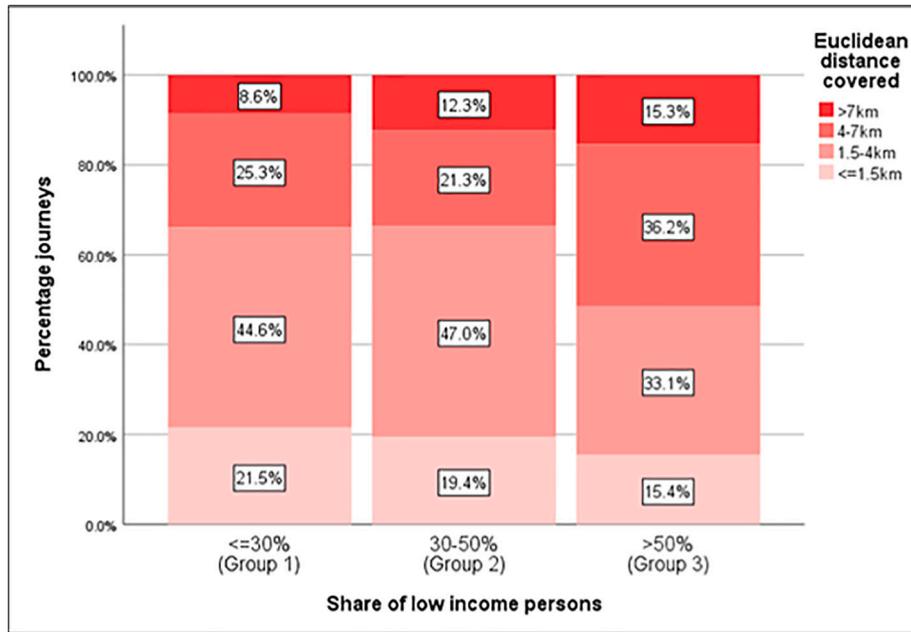


Fig. 8. Distribution of Euclidean distance covered by income profile of transit stops.

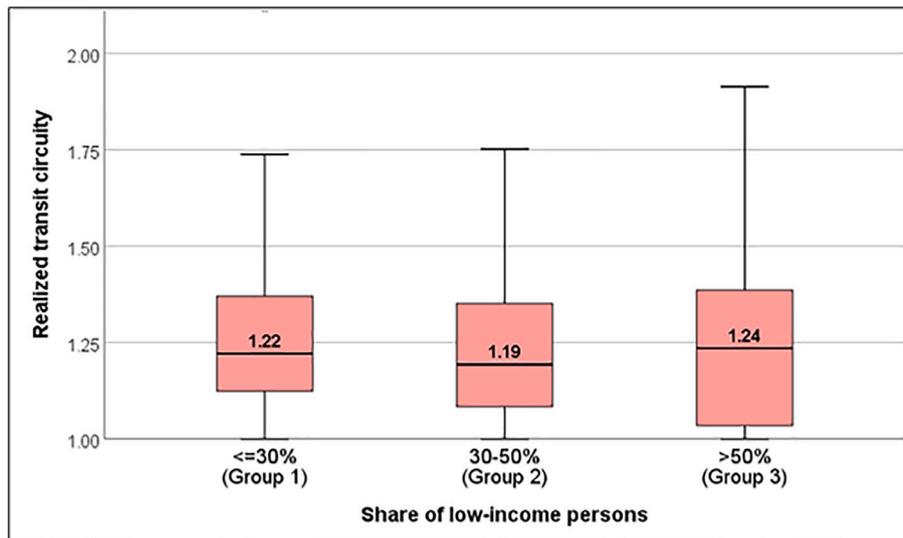


Fig. 9. Distribution of circuitry by income profile of transit stops.

Table 1
Spatial error model estimation results.

| Variable | Coefficient | Std. error | Probability |
|---|-------------|------------|-------------|
| Dependent variable = Log (Circuitry) | | | |
| Constant | 0.474 | 0.029 | 0.000 |
| Percentage share of high-income persons | -0.003 | 0.001 | 0.001 |
| Dummy for Amsterdam North | 0.185 | 0.029 | 0.000 |
| Average Euclidean distance (km) | -0.032 | 0.004 | 0.000 |
| Spatial coefficient on errors (Lambda) | 0.536 | 0.040 | 0.000 |
| Number of observations = 472 | | | |
| Log likelihood = 347.77 | | | |
| AIC = -687.55 (AIC for OLS = -587.87) | | | |

All dependent variables are found to be statistically significant. As expected, transit stops in Amsterdam Noord have 20.3% (=exp (0.185)-1) higher circuitry on average compared to the rest of the city, all else being equal. The average Euclidean distance traveled for a transit stop

represents the proximity to opportunities of the transit stop. For every km increase in Euclidean distance, the average transit circuitry of a stop decreases by 3.2% – implying the longer transit routes tend to be more direct. However, even when controlling for the Euclidean distance, stops in higher income areas are associated with lower circuitry values. For every percent increase in share of high-income residents, the circuitry decreases by 0.3%, all else being equal. The share of high-income residents within the study area ranges between 3% and 54%, implying a maximum circuitry difference of up to 14% between neighborhoods due to income effect.

The regression analysis confirms that the transit routes being used by travelers from high-income areas indeed have lower circuitry for the same Euclidean distance covered, even when controlling for Amsterdam Noord and spatial dependence. This could be a result of two contributing factors. Firstly, the circuitry of routes serving high-income areas could be low. But it could also be that the destinations of travelers from high-income areas have more direct routes. Although both scenarios

highlight the underlying inequity, different solutions are needed for each. To confirm if there are differences in the types of destinations visited, we analyzed the distribution of destinations for each of the three income groups. However, no substantial differences were found between travelers from the three groups, suggesting that the differences in circuity by income observed in the data are primarily due to the routes serving these areas as opposed to the differences in destinations.

4.3. Impact on travel times and fare paid

As a combined effect of the distribution of circuity and Euclidean distance, travelers from predominantly low-income areas in Amsterdam do indeed have longer transit journeys on average compared to the rest of travelers (Fig. 10). The share of longer journeys (>8.5 km) is found to increase with the share of low-income residents. Moreover, substantial difference is found in the median journey length for group 3 (4.9 km), compared to group 1 (3.9 km) and group 2 (3.6 km). Overall, the differences between group 1 and 2 are found to be less pronounced than those of either of them with group 3, as in case of the distribution of Euclidean distance.

Transit fare in Amsterdam is calculated based on the network distance traveled, with the fare increasing linearly with distance. The journey length distribution in Fig. 10 hence implies that travelers from lower income areas travel longer on average, and in turn pay a higher fare per trip, before accounting for redistribution measures such as special subscriptions and concessions. The circuity of transit networks is a function of the network design. It can be argued that for a horizontally equitable distribution of transit services, every traveler in the network should pay the same fare per Euclidean distance covered, which means equal distribution of circuity over the network. Here we evaluate the horizontal equity of the network in terms of circuity using Gini coefficient. Fig. 11 shows the Lorenz curve with the share of accumulated circuity by share of population, and the Gini coefficient. The Gini coefficient of 0.11 indicates that the fare paid per Euclidean distance traveled is slightly unevenly distributed in the network. In relative terms, it is not possible to comment on how fair this distribution is, as such an analysis of circuity has not been undertaken for any other network yet.

Transit circuity is expected to also impact the observed travel times. To analyze this relationship, we normalize the travel time by the

Euclidean distance covered. Fig. 12 shows the distribution of this metric with the realized transit circuity across the network. In the absence of congestion effects, as the circuity of journey increases, longer time is spent on average to cover the same Euclidean distance, which is found to be the case for Amsterdam network.

However, when we examine the distribution by income categories (Fig. 13), the travel time per Euclidean distance covered does not follow the trend of circuity distribution, with group 2 having the highest median value (4.2 min/km), followed by group 1 and group 3 (4.0 and 3.8 min/km, respectively). Perhaps for group 1 and 2, although the circuity of routes is lower, other network characteristics such as shared right-of-way, on-road congestion and crowding compensate for the reduced travel time. Similarly, on routes with higher circuity serving lower income areas, the vehicle speeds may be higher. In the case of Amsterdam, tram services have lower speed in the historical core which is characterized by higher income levels. In contrast, low income areas are often located in proximity to tram corridors with a designated right-of-way or metro lines - especially the high circuity categories (>2) have a large share of metro (see Fig. 5), and therefore high speeds.

4.4. Discussion

The circuity of transit networks has an impact on the distance traveled in the network. For Amsterdam network, the distribution of circuity favors the higher income groups, exacerbating the differences in distance traveled by income groups. This directly impacts the fare paid by the travelers. The Gini coefficient quantifies the equity of distribution of fare paid for every km of Euclidean distance covered under the current distance based fare structure. The circuity patterns observed in a network are a function of network design, which is often derived from a city's natural terrain and evolution of urban form. By improving the circuity of transit routes serving low income areas, the distribution of fare paid per Euclidean distance covered can be made more vertically equitable. This may however come at the cost of compromising other network planning considerations. Alternatively, with an egalitarian perspective, fares could be charged based on the Euclidean distance covered instead of network distance to address equity concerns.

This study highlighted the contribution of network design to the inequity of fare paid in a network, and how it can be used to address equity concerns. Camporeale et al. (2017) highlight that equity concerns

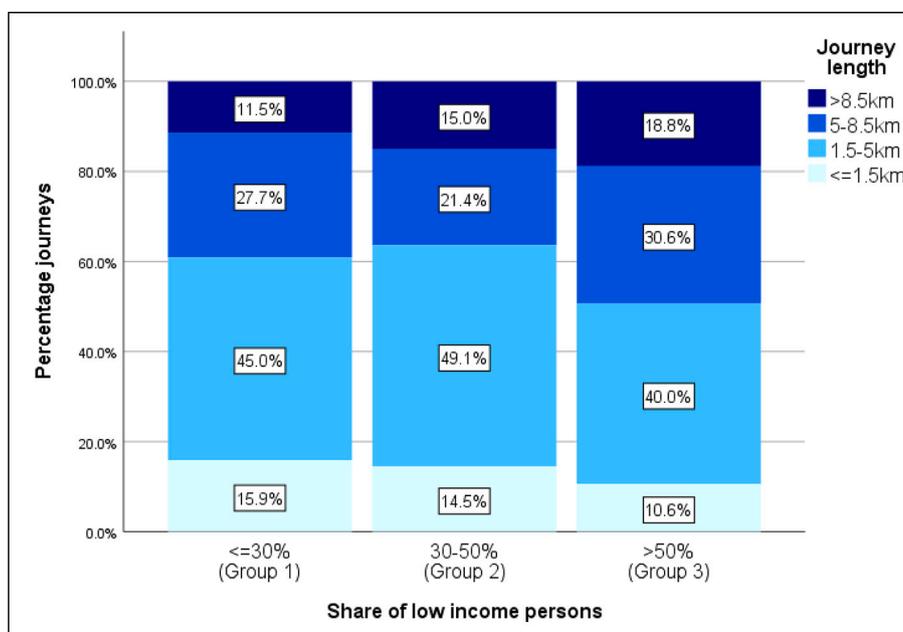


Fig. 10. Distribution of journey lengths by income category.

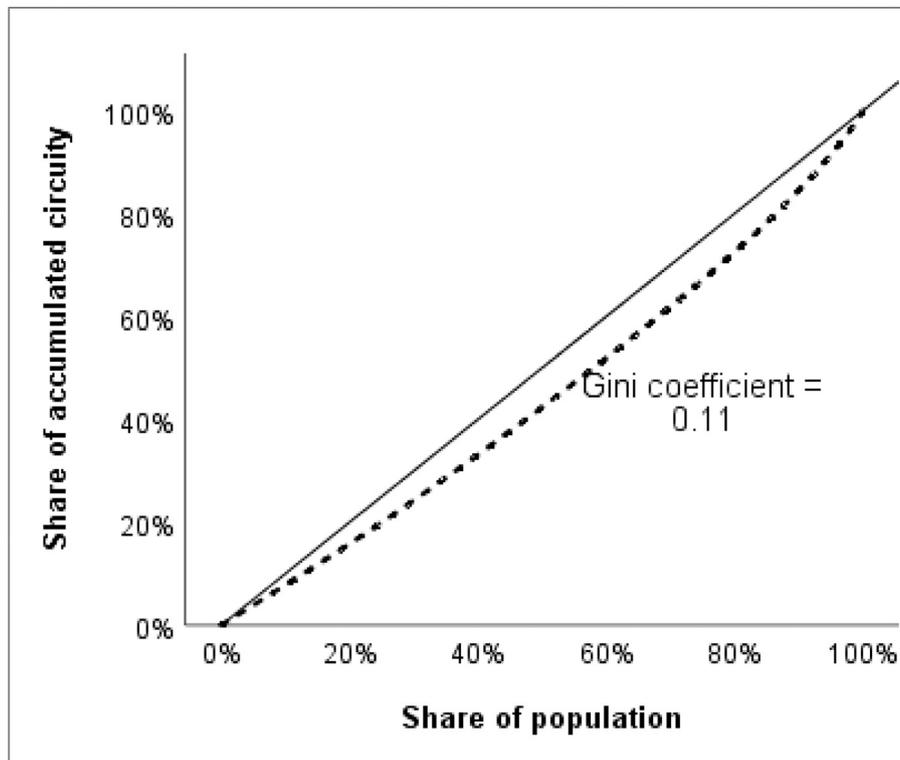


Fig. 11. Lorenz curve and Gini coefficient for distribution of transit circuitry in the network.

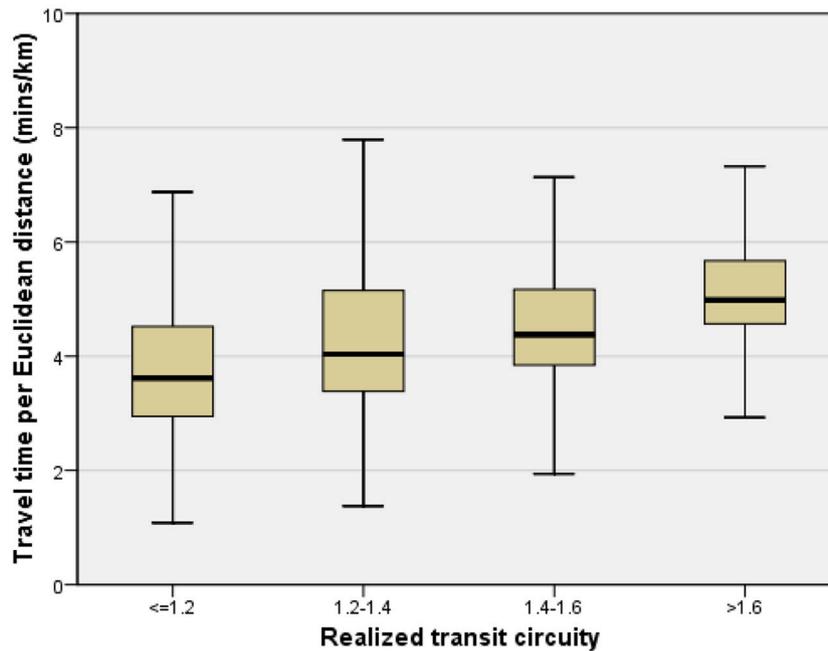


Fig. 12. Travel time per Euclidean distance and realized transit circuitry.

have traditionally been ignored during network planning, and have been “in the best cases an afterthought during service provision”. The process and analysis used for this study can be adapted for different network configurations (in combination with the fare structures) to assess the equity of a system. Where it is not possible to reduce circuitry, other mitigation measures could be applied to compensate for the disparity caused by circuitry of routes, such as different fare structures (based on Euclidean distance or flat fare). A key advantage of measuring equity

using circuitry is that such an analysis not only highlights the problems, but also provides insight on possible solutions. Incorporating equity concerns at the network design stage can lead to improved equity of outcomes such as fare paid and travel times.

Ridership and coverage are considered two of the primary goals of public transport, which are often opposing (Walker, 2008). Lower circuitry is typically associated with shorter travel times (as also in the case of our study) leading to higher ridership, but lower coverage.

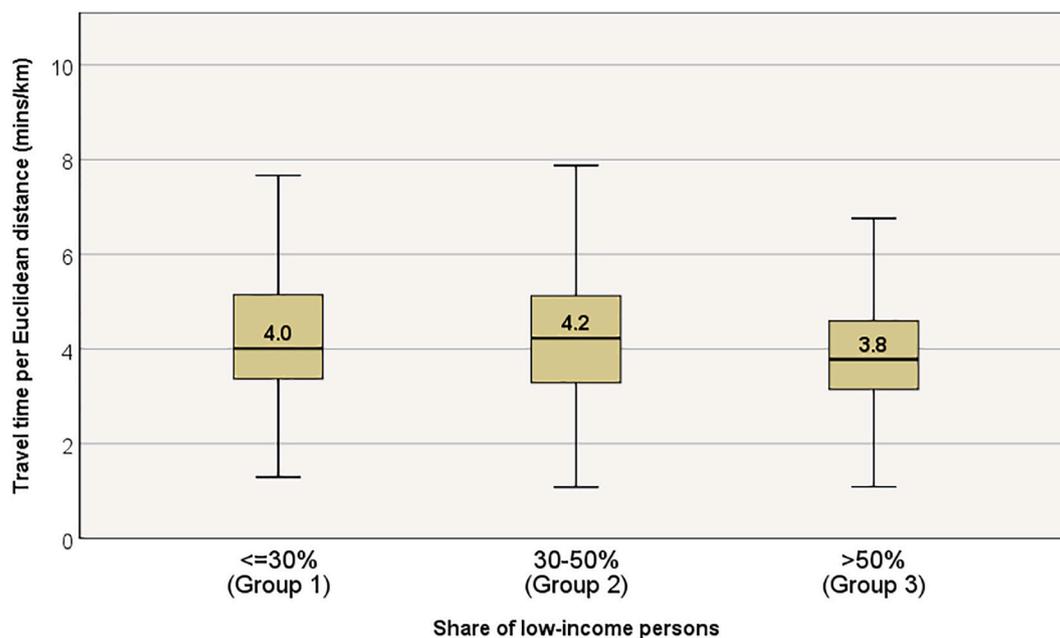


Fig. 13. Travel time per Euclidean distance by income category.

Conversely, higher circuitry can provide more coverage but it comes at the cost of longer travel times which can negatively impact ridership. Coverage goals are often social ones relating to serving the needs of disadvantaged population, or providing geographic equity of transit provision (Walker, 2008). However, as shown in our study, the higher circuitry required to fulfil these goals can result in inequity of distance traveled and fare paid. Eventually, these trade-offs need to be weighed against each other based on the planning goals for the network under consideration. To that end, it will be useful to have more empirical research looking at these trade-offs in greater detail in the future.

Although smart card data enabled an extensive analysis of circuitry by providing information on all journeys undertaken in the urban network, some limitations cannot be ignored. Firstly, the smart card data used in this study does not distinguish between tourists and residents. This may impact some results of the study as tourists are more likely to travel in the higher income areas in the city center, and tend to make shorter journeys. This might have overestimated the number of shorter trips associated with high income residents in our analysis. However, the proportion of tourist journeys is expected to be small, especially in the AM peak period (Central Bureau of Statistics (CBS) Netherlands, 2020b). Secondly, since our data is restricted to only the urban transit network of Amsterdam (excluding regional buses/trains), we cannot differentiate between travelers coming into Amsterdam from neighboring regions and trips originating within the case study network. People traveling to Amsterdam by train or regional bus services are now assigned to the income levels associated with the station where the traveler transfers to the urban network. Since people who need trains or regional bus services to reach Amsterdam have larger travel distances (and therefore higher fares), this assumption may have underestimated journey lengths. Thirdly, we have used a commonly used catchment area radius of 400 m (El-Geneidy et al., 2014) for assigning income and our results are subject to this assumption. The analysis could be improved with a more precise value of this catchment area obtained from additional data sources. Lastly, our analysis was restricted to morning peak period due to the unavailability of income information for evening/off-peak journeys. However, considering that low-income persons often travel during off-peak periods, including such time periods can provide a more comprehensive picture of equity and could be undertaken as further research. This would however require additional data sources to estimate the income levels for off-peak journeys.

5. Conclusion

This study examined the contribution of transit circuitry to the disparity in distance traveled between different income groups in a network. Furthermore, its implications on the travel times and the fare paid in a distance-based fare system were discussed. This was done for the case study of the multi-modal urban transit network of Amsterdam, using the demand data from smart card paired with the neighborhood level income data.

Travelers from predominantly lower income areas in Amsterdam were found to have more circuitous journeys compared to the rest of the travelers. For the same Euclidean distance covered and residential location with respect to the river (north/south), circuitry was found to decrease with an increasing share of high-income residents, when controlled for spatial-autocorrelation. This exacerbated the already existing differences in Euclidean distance traveled between the income groups. As a result, travelers from lower income areas need to travel longer distances and pay a higher share of the fares in the network. The Gini coefficient also indicates a horizontal inequity in the distribution of fare paid per Euclidean distance. However, the differences in travel time (per Euclidean distance) were in favor of lower income areas (3.7 min/km as opposed to 4–4.2 min/km for other areas). These are presumably compensated in the Amsterdam case by the various network characteristics experienced by the respective groups.

Overall, this study highlighted the role of transit network design in determining the equity outcomes of travel time and fare paid in a network. The equity outcomes in a network depend on the specific interaction between the land-use distribution, transit network design, and the fare policy employed. As further research, it will be valuable to compare the results obtained in this study with those for other cities, and could be utilized to compare different network structures or fare policies in terms of equity.

Declarations of interest

None.

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