Study of the Accessibility Inequalities of Cordon-Based Pricing Strategies Using a Multimodal Theil Index

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The implementation of an appropriate pricing policy in an urban area could alleviate both environmental and congestion problems by encouraging a shift towards more sustainable modes of transportation. However, any positive net social welfare balance delivered by the policy can hide unacceptable regressive effects. Therefore, it is crucial to investigate any change in relative levels of accessibility among different categories of transport network users.

This study focuses on the application of a cordon-based congestion pricing scheme on a multimodal network, where private cars and public transportation coexist, and includes a sensitivity analysis by varying the size of the charging area and the amount of the toll, for a monocentric urban reality. Taking into account an elastic demand associated with each proposed charging scenario, the related distributional effects are explored using the Theil index, with a quantitative assessment of the inequalities in the accessibility variations across the users of the network.

Keywords: multimodal inequalities; accessibility disparities; road pricing policy; cordon-based scheme; elastic demand.

1. Introduction

The quest for more sustainable and environmentally friendly cities is one of the major challenges of our century (Souche, Mercier, and Ovtracht 2016). Mitigation of traffic congestion is a fundamental step towards better urban quality. Indeed, prolonged travel times due to road congestion increase fuel consumption and pollution, and hinder economic growth, making cities less sustainable (Stopher 2004).

In this context, congestion pricing is a traffic management measure that has been often proposed and implemented in different cities (e.g. London, Singapore, and Stockholm, among others). Tolls are levied to use links or areas of urban road networks to influence travellers' behaviour – encouraging changes of departure time, route or mode – and recover the external costs generated by mobility (Zheng et al. 2012). Pricing has proven able to reduce road congestion, at least in the short term (Santos and Shaffer 2004).

In this paper, we focus on the inequalities that arise with congestion charges. Promoting equality is an increasingly important objective of public policies. In addition, more equitable approaches can ease the implementation of such unpopular measures. Often residents oppose this kind of policies, seen as harming their interests and not fair to the majority of them (Hensher and Puckett 2007; Song, Yu, and Pan 2016). Therefore, we suggest a preliminary study of the inequalities associated with a pricing measure, based on the analysis of main features of the transport network and the socio-economic characteristics of the study area, to guarantee that the beneficial effects of the pricing policy are not attained at the cost of increased disparities among travellers.

The paper presents a method to analyse the distribution of multimodal accessibility (which should be the concern of urban and regional planners instead of other mobility-related factors (Straatemeier 2007)) deriving from the application of a congestion price scheme on an urban network, across different social groups and geographical districts of the city. We suggest the use of the Theil index (Theil 1967), an indicator implemented in other fields to assess the level of inequalities existing in a given context. We propose to use it for planning purposes, to evaluate the implications in terms of inequalities of different pricing scheme designs.

The aim is to provide urban planners and decision-makers with a tool to realize the transport inequalities arising from the introduction of new policies/investments intended to make cities more sustainable.

The remaining part of the paper is structured as follows: Section 2 summarises existing knowledge on pricing policies and accessibility evaluations. Section 3 discusses the accessibility and the inequality measure that we use. Section 4 describes our methodology. Section 5 presents a sensitivity analysis on a test monocentric urban reality. Section 6 ends the paper with some conclusive remarks about the implications of this analysis.

2. Implementation of a congestion pricing scheme and equality issues

The road congestion pricing has been proposed as one of the most effective strategies to mitigate traffic congestion in urban realities and raise social welfare in society (Santos 2004; Maruyama and Sumalee 2007; ITF 2018). Different pricing schemes could be applied on the network; however, the cordon-based system is probably the most studied regime in the literature, due to its high potential to be actually implemented in real contexts (May et al. 2002). It can be defined as a system which charges vehicles when they pass by some points in the road network: these points can be isolated or, more usually, grouped into continuous loops around defined areas (May et al. 2002). Cordon-based schemes are relatively simple to model considering tolls as additional delays (i.e. increased travel times) for the drivers traveling on the charged roads (Milne 1997).

The introduction of a road pricing scheme may potentially produce different effects. They can be mainly grouped into four categories (Eliasson and Mattsson 2006):

- higher travel costs for the car drivers that pass by the charged areas;
- different users’ travel behaviours to avoid the toll;
- shorter travel times for the car users traveling in the charged areas;

- revenue generation, to be calculated net of the costs of implementing the pricing scheme (see Goodwin (1989), Small (1992) and Caggiani et al. (2017, 2019) for a discussion of ways to redistribute revenues on transportation-related projects).

Despite the potential to generate benefits, pricing measures have often encountered low public and political acceptance, also because of insufficient consideration of distributional impacts (costs and benefits) across different population groups. Kocak et al. (2005), for instance, stressed the need for new methods to increase the acceptability or charging schemes, while not compromising the desired outcomes and effectiveness. Therefore, it is crucial to develop methods to include the assessment of equity impacts in the design of pricing schemes.

In summary, the word equity in a transport context embraces the concept of fair or equal distribution of impacts (either costs and benefits) across all groups of network users (Litman 2016). This distribution can be seen from a vertical perspective, linked to classes of travellers with different characteristics (for instance, in terms of income, age, sex, ethnicity, access to a car, travel flexibility, etc.), that could require a different share of transport resources according to their socio-economic status. On the other hand, a horizontal perspective implies the analysis of the distribution of impacts across different spatial locations or trip movements. Recently, several studies have appeared linking setting up an urban toll to the derivation of inequality impacts. Such studies usually are based on inequality indicators taken from the economic field.

Among others, it could be worth mentioning Sumalee (2003) who adopted the Gini coefficient to measure the spatial equity impacts -across different zones- deriving from the implementation of different charging cordon designs. Bonsall and Kelly (2005) discussed the implications of social exclusion and equity issues in the context of road user charging and proposed a new technique to establish the impacts on vulnerable population groups of six different pricing scheme in Leeds.

Karlström and Franklin (2009) examined the equity effects of the Stockholm congestion trial in 2006, observing the changes in travel behaviour, and then estimating the differences in welfare effects across different demographic groups. Eliasson (2016) discussed this issue from a consumer perspective, looking at the amount of the toll that each individual has to pay, how much travel time is saving, the benefit of the recycled revenues. More recently, Souche, Mercier, and Ovtracht (2016) used several indicators (Gini, Theil and Atkinson indices) to measure the changes in the concentration of income and gravity-based accessibility, simulating the introduction of a pricing cordon in the Lyon Metropolitan area.

In this paper, we focus on the multimodal accessibility (by private and public transport) among different traffic zones and different segments of the population. We aim at analysing the changes in this accessibility, and quantitatively assessing the inequalities of these changes, after the introduction of a cordon-based pricing scheme on the network.

3. Accessibility evaluations and distributional effects: the Theil index

Measuring inequalities in the distribution of accessibility after the implementation of a pricing strategy is crucial since accessibility determines the participation of different social groups to daily activities (economic, social, political, and so on) or, on the contrary, gives rise to social exclusion (Levitas et al. 2007). In fact, recent literature focuses not only on (the equality of) access to the transport system itself but also on the access to activities and opportunities through the transport network (Carrasco and Miller 2009; Páez et al. 2010; Lucas 2012).

Accessibility can be defined as the extent to which land-use and transport systems enable (groups of) individuals to reach opportunities (jobs, shops, public transport stations and stops, health facilities, and so on) by means of a (combination of) transport mode(s) (Geurs, Patuelli, and Dentinho 2016). Different types of accessibility measures have been introduced over the past decade. The debate is still on-going on how they relate to one another, and on which one is the most suitable in each situation (LaMondia, Blackmar, and Bhat 2011). Measures of accessibility are commonly grouped into three categories: cumulative, gravity-based and utility-based (LaMondia, Blackmar, and Bhat 2011). In this paper, we suggest the use of a gravity measure, often preferred because it can be calculated and interpreted in a relatively easy way (Geurs, Patuelli, and Dentinho 2016). Gravity-based accessibility measures include an attraction and a separation factor (impedance) and discount opportunities when time and/or distance from the origin increases.

In particular, we refer to the following expression (Hansen 1959), Eq. (1):

$$\mathrm{A}_o = \sum_d \mathrm{O}_d \mathrm{f}(\mathrm{C}_{od}) \tag{1}$$

where A_o is the total accessibility of the origin zone *o*, O_d measures the opportunities (jobs, shops, public transport stations and stops, health facilities, etc.) that can be found in the destination zone *d*, C_{od} is the cost of traveling from the origin to the destination, and $f(C_{od})$ is an impedance function of the separation between *o* and *d*. It can be easily noted that the data required to calculate this index are: size and the location of the opportunities under investigation, and travel time or distance between the zones in the considered study area.

To assess the distributional effects across different zones and socio-economic groups) of a pricing scheme, an appropriate indicator need to be selected. In this paper, we have opted for the adoption of the Theil coefficient, considered the most sensitive in measuring changes at the ends of a distribution. Its main advantage and the reason for its popularity when assessing inequalities is that it can be perfectly decomposed *within* and *between* any arbitrarily defined population subgroups, without any residual term. To assess the differences in the distribution of the accessibility to a certain destination across the population of a given study area, the Theil (T) coefficient can be calculated as:

$$\mathrm{T} = \frac{1}{\mathrm{P_T}} \sum_{j=1}^{n} \frac{\mathrm{A}_j}{\overline{\mathrm{A}}} \ln\left(\frac{A_j}{\overline{A}}\right) \tag{2}$$

where $\mathrm{P_T}$ is the total population made up of *n* individuals *j*; A_j is the accessibility of each individual *j* to the area of concern; $\overline{\mathrm{A}}$ is the average per capita accessibility in the study area. Theil's measure falls between 0 in the case of perfect equality and ln(*n*) for perfect inequality. It can be easily proven that, if the population is divided into *m* groups *i* (for instance, *m* = 2: rich and poor) each of which including n_i individuals, the Theil coefficient can be decomposed in two components:

$$\mathrm{T} = \mathrm{WITHIN} + \mathrm{BETWEEN} = \sum_{i=1}^{m} \sum_{j=1}^{n_j} \left(\frac{1}{\mathrm{P_T}} \frac{\mathrm{A}_{ij}}{\mathrm{A}_i}\right) \ln\left(\frac{\mathrm{A}_{ij}}{\mathrm{A}_i}\right) + \sum_{i=1}^{m} \left(\frac{\mathrm{p}_i}{\mathrm{P_T}} \frac{\mathrm{A}_i}{\overline{\mathrm{A}}}\right) \ln\left(\frac{\mathrm{A}_i}{\overline{\mathrm{A}}}\right) \tag{3}$$

where p_i is the number of people belonging to group *i*, A_j is the average per capita accessibility of the group *i*, and A_{ij} is the accessibility of the individual *j* belonging to group *i*. The contribution given by each group (terms in the sum) can be either positive (if the average accessibility A_j is greater than $\overline{\mathrm{A}}$) or negative (in the opposite situation). In the former case, the status of group *i* contributes to increasing inequality, in the latter instead it improves equality. In any case, the positive terms are always larger than the negative ones, so that the overall Theil is always positive.

If, on the one hand, limited claims can be made about the absolute values scored by the Theil index and its components given that they depend on the number of groups; on the other hand, what matters is the possibility to compare these values over time, space, or population groups. Calculating the Theil coefficient for different cordon-based pricing schemes (i.e. schemes differing by the size of the charged area and/or amount of toll), planners and decision-makers can identify the optimal strategies in terms of reducing inequalities.

4. How to assess inequalities in urban multimodal access

In this section, we present a method to assess the effects on the multimodal accessibility of a road pricing scheme. Here multimodal means that we assume the presence of both private cars and public transport in the analysed area. In this area, a cordon-based pricing scheme is applied, with tolls levied in a daily time window Δt (e.g., peak hours on weekdays). We assume that only private cars are subjected to the toll payment and that the demand is elastic (Nuworsoo, Golub, and Deakin 2009).

In this context, we need to investigate the relationship between any particular configuration of the charge and the associated modal split and traffic flows on the network. In fact, the introduction of a cordon-based pricing scheme affects the travel costs of private car drivers, leading to changes in the choices of network users that may switch mode or path. We propose to use a four-step trip-based travel-demand model (Cascetta 2009) to predict the average number of trips.

In a multimodal context like ours, the accessibility A_o for every origin zone can be defined as the sum of different components, one for each available transport mode t (e.g. private cars, trains, buses, metro and so on, $t \in [1, \ldots, k]$), characterised by a specific travel cost $C_{od,t}$. To take into account the demand changes associated to every pricing scheme configuration, we propose to weight each component for the actual number of people traveling from *o* to *d*, in the time interval *Δt*, by the transport mode *t*. Therefore, we need to know the Origin-Destination (OD) matrix on the network for each transport mode *t* considered in the analysis, obtained as the output of the four-step travel-demand model.

Relying on Eq. (1), we calculate the accessibility A_o of the origin zone *o* towards all the destinations *d* using the Eq. (4) below:

$$A_o = \frac{\sum_d \sum_{t=1}^{k} OD_t \cdot O_d f(C_{od,t})}{OD_{TOT}} \tag{4}$$

Note that we suppose that the transport planner/policies adapt the public transport supply to the newly occurred needs of the population - that is, although the transit routes do not change, the bus frequencies are assumed sufficient to serve the potential demand increase induced by the pricing strategy. Therefore, any users shifting from private cars to a public transport mode contributes to mitigating congestion.

For any pricing scenario, the effects on the multimodal accessibility defined by Eq. (4) (both from a social and a geographical perspective) can be assessed and discussed using the Theil coefficient, described in the previous section. A sensitivity analysis, able to take into account the size of the charged area, the amount of the toll, the achieved modal shift and the inequalities in the accessibility to any relevant opportunity, has to be performed to provide planners and decision-makers with the knowledge they need before applying a particular policy on the network

5. Sensitivity analysis in a monocentric urban reality

In this section, we simulate the application of a cordon-based congestion scheme to a test case study and evaluate its impacts on accessibility inequalities in comparison with the starting scenario (before pricing), used as a benchmark.

5.1 Case study

Our simulated urban area (the same adopted in Caggiani, Camporeale, and Ottomanelli 2017a) is a grid of 3.0 km x 3.6 km, with a transport network with 693 nodes and 2616 arcs (Figure 1). It reproduces a generic urban area with blocks (having an alternate module of 150 m and 75 m) and natural areas. We assume a monocentric reality, in which congestion in the central districts can be alleviated by a pricing cordon. In each charging scenario, the tolled links are those intersecting a circumference centred in the grey dot in Figure 1. Two transport modes operated in the study area, private cars and buses. There are three bus lines, denoted by dashed coloured lines in Figure 1.

The area is divided into 29 zones ξ (delimited by continuous lines in Figure 1), each with a centroid considered as origin and destination of the trips. Individual trips are supposed to take place to exploit job opportunities.

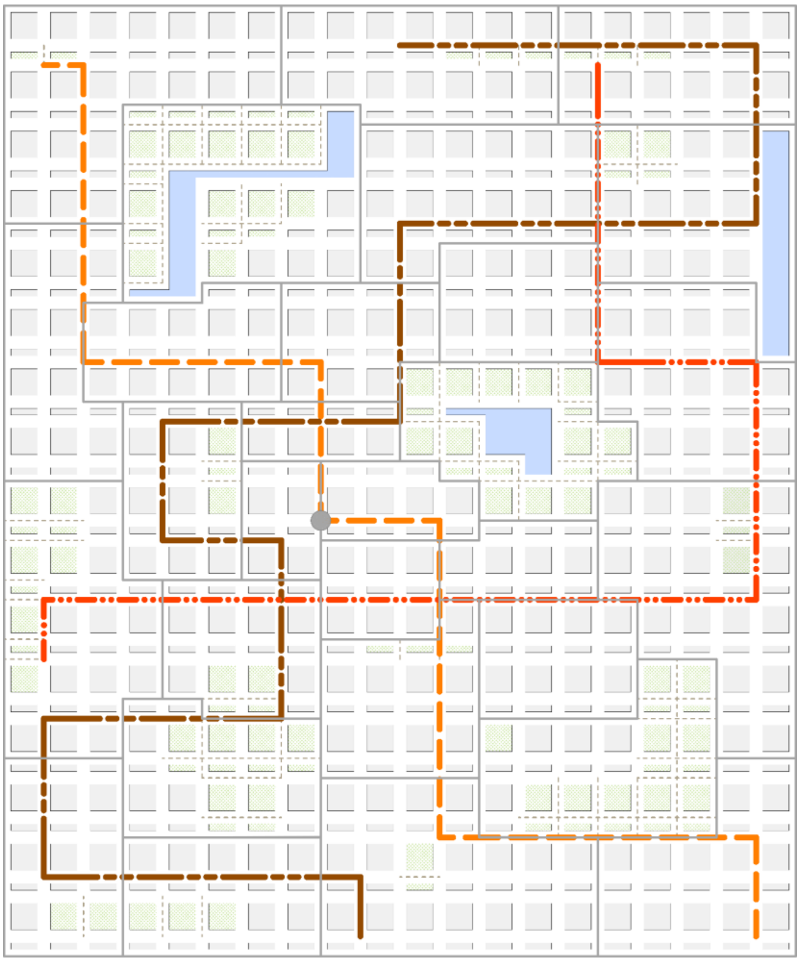

Figure 1. Test network.

Table 1 shows the socioeconomic attributes of each zone, that is, residing population Pop_{ξ}, workers W_{ξ} (individuals living in ξ and having a job), number of employees E_{ξ}, and residing disadvantaged people x_y. People working in a zone do not necessarily reside within the borders of the test area, but simply have a job located in one of the zones. 'Disadvantaged' refers generically to people in need of better access. The disadvantage can arise from poor access to different kinds of goods and services, e.g. jobs, health services, recreational facilities, education. Different population groups in the same area may experience poor access to different types of goods and services. In practical applications, disadvantaged groups are often identified by means of specific sociodemographic characteristics of the population or of aggregated indexes like the Scottish Index of Multiple Deprivation in Scotland (https://www2.gov.scot/Topics/Statistics/SIMD). Since our focus is on demonstrating the use of the Theil index on a simulated urban area, we do not specify the cause of the disadvantage but we assume that the distribution of the disadvantaged population is known. In particular, we consider the disadvantaged population randomly distributed across the zones. Our case study includes two population groups (labelled as 'advantaged' and 'disadvantaged'). However, the method we propose can deal with any number of groups, the only the difference being the number of addends in the sums in Eq. (3).

Table 1. Demography of each traffic zone.

Zone	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***
Pop_ξ	797	944	336	819	658	1331	543	869	1284	1772	1201	456	1517	1514	1885
W_ξ	343	434	239	647	553	705	434	382	706	1258	817	223	1123	818	886
E_ξ	203	426	526	176	182	443	448	95	342	730	241	448	783	620	698
x_y	192	74	119	569	72	550	321	141	501	994	466	136	269	458	186

Zone	***16***	***17***	***18***	***19***	***20***	***21***	***22***	***23***	***24***	***25***	***26***	***27***	***28***	***29***
Pop_ξ	1610	778	1581	1636	1693	67	397	230	1458	447	396	822	318	771
W_ξ	1159	513	933	1047	626	57	147	110	671	174	139	493	156	362
E_ξ	595	476	391	521	441	247	424	318	458	118	1453	480	1289	987
x_y	927	169	233	461	338	45	66	23	342	126	64	419	64	43

In the four-step trip-based travel-demand model system, the following parameters are considered (see Caggiani, Camporeale, and Ottomanelli 2017b for more details about each sub-model):

- in the trip production model, the trip production rate is assumed equal to 60% (of the individuals residing in that area and traveling to work);
- in the distribution model, the two attributes considered for the calculation of the systematic utility are the number of employees (related to the attractiveness of the destination zone), having $\beta_{empl} = 0.9725$, and the distance between pairs of centroids (to quantify the travel costs between origin and destination), having $\beta_{dist} = 0.7025$;
- in the mode split model, we consider two alternatives, car and bus. The attributes considered for these modes of transportation are travel time (min) ($\beta_{min} = 1.6142$, both for bus and car), monetary costs (€) ($\beta_{€} = 0.3338$, both for bus and car) and alternative specific constant (ASC) (or modal preference attribute) (we set ASC = 0 for cars, and 1 buses, with $\beta_{ASC} = 0.8$). Moreover, we assume that only one transfer is allowed, when traveling by bus, to reach the desired destination, corresponding to a penalty of 5 minutes.

The average speed of the vehicles on the network has been set equal to 20 km/h for cars, and 10 km/h for buses. In terms of monetary cost, a cost of 0.60 €/km is assumed for car travels and a cost of 1 € for the bus ticket. The car occupancy rate is supposed equal to 1.

The concept of generalised time has been discussed since 1974, when Goodwin (1974) described how the total amount of travel depends on income. Road pricing is usually expected to receive more support from higher income groups, as their value of time is supposed to be higher, and their marginal value of income generally lower (Schade and Schlag 2003). However, as highlighted by Börjesson and Eliasson (2014), the value of time is subject to large variations, related to both traveller traits and trip characteristics. Variations of values of time should be accounted for in the analysis of equity impacts when data are available. In the following, we do not consider them to make the illustration of the properties of the Theil index in the context of scheme design less complicated.

In this context, in the calculation of the accessibility A_o for each traffic zone, opportunities at the destination (O_d) coincide with the number of employees in that zone, while the impedance function $f(C_{od})$ is calculated using the following decay function (Vale and Pereira 2017):

$$f(\mathrm{C}_{od}) = \exp^{-\beta t_{od}} \tag{5}$$

Considering the three attributes of the transport modes (time t_{od}, monetary costs c_{od} and ASC), the accessibility from an origin towards all the destinations is:

$$\mathrm{A}_o = \frac{\sum_d \sum_{t=1}^{2} \mathrm{OD}_t \cdot \mathrm{E}_d \cdot \exp^{-(\beta_{min,t} t_{od,t} + \beta_{€,t} c_{od,t} + \beta_{ASC,t} \mathrm{ASC}_t)}}{\mathrm{OD}_{car} + \mathrm{OD}_{bus}} \tag{6}$$

where the OD indicates the overall demand from O_d served by each transport mode.

5.2 Analysis of the accessibility inequalities: social and geographical effects

In order to illustrate the impacts on the inequalities in the multimodal accessibility caused by the implementation of a pricing scheme, we perform a sensitivity analysis in which we change the size of the charged area progressively increasing the radius of the circumference centred in the grey dot of Figure 1 (from 0 km – i.e. the case with no congestion charge – to 1 km) and the amount of the toll (from 1 € to 10 €).

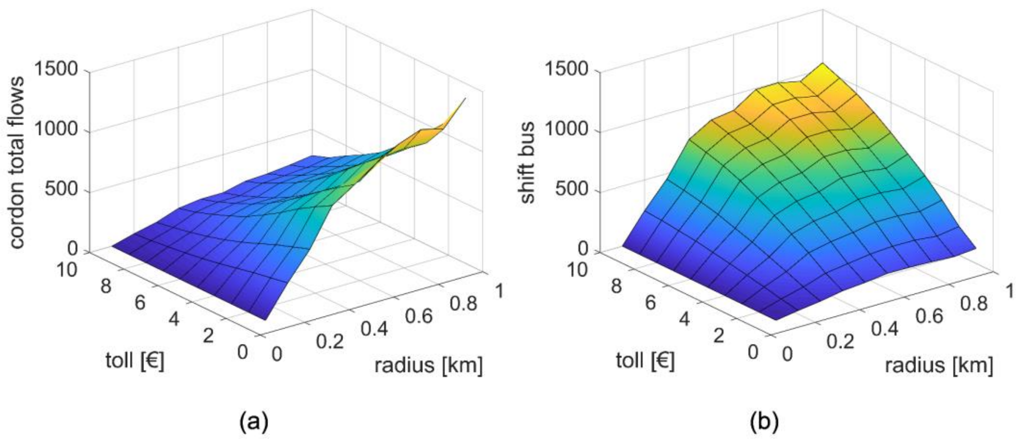

Figure 2. (a) Total car flows passing through the cordon while varying the size of the charged area and the amount of the toll; (b) Number of users that switch transport mode (from car to bus) after the implementation of a pricing strategy on the network.

In Figure 2a, we can see the trend of the total flows of cars traversing the cordon. If the toll is low, car drivers still prefer to traverse the cordon and pay the toll in order to reach their destinations, even when the radius of the charged area increases (we note that when the radius of the cordon increases, the intercepted flows increase because larger areas are included in the charged zone). As the toll rises, more people prefer the public transport mode to reach their jobs (Figure 2b) and so the total car flows on the cordon drop steadily.

Table 2 reports the values of the global Theil index for each charging scenario, i.e. the inequalities in the distribution of the accessibility from each origin zone toward all the others in the network. Insights for designing the scheme can be derived from the comparison of the Theil indexes corresponding to different scheme configurations (as in this case) or population groups, and/or analysing the variations in space and time. We note that instead no useful suggestion can be drawn by consideration of single Theil index values. As expected, the Theil values tend to grow as the radius increases since more travellers are affected by the toll. Larger tolls mean greater differences in accessibility between people living inside and outside the cordon.

The inequalities on the network grow as more users are embodied by the cordon, as greater differences in accessibility can be measured between the individuals living inside and those outside the pricing scheme.

Table 2. Theil values for each charging scenario.

Radius[km]	***0.1***	***0.2***	***0.3***	***0.4***	***0.5***	***0.6***	***0.7***	***0.8***	***0.9***	***1***
Toll [€]										
1	0.0053	0.0051	0.0053	0.0068	0.0074	0.0079	0.0097	0.0108	0.0123	0.0132
2	0.0053	0.0051	0.0055	0.0082	0.0094	0.0102	0.0141	0.0160	0.0192	0.0214
3	0.0053	0.0051	0.0057	0.0093	0.0110	0.0119	0.0175	0.0201	0.0248	0.0280
4	0.0053	0.0051	0.0058	0.0099	0.0119	0.0130	0.0197	0.0226	0.0284	0.0322
5	0.0053	0.0051	0.0058	0.0102	0.0123	0.0135	0.0207	0.0239	0.0302	0.0343
6	0.0053	0.0050	0.0058	0.0103	0.0124	0.0136	0.0210	0.0242	0.0308	0.0350
7	0.0053	0.0050	0.0058	0.0102	0.0123	0.0135	0.0209	0.0241	0.0307	0.0349
8	0.0053	0.0050	0.0058	0.0101	0.0121	0.0133	0.0206	0.0238	0.0303	0.0345
9	0.0053	0.0050	0.0057	0.0100	0.0120	0.0131	0.0202	0.0233	0.0297	0.0337
10	0.0053	0.0050	0.0057	0.0098	0.0118	0.0129	0.0199	0.0229	0.0292	0.0332

The possibility of decomposing the Theil index in its *within* and *between* components allows getting more insights on the accessibility of two population subgroups, namely ‘advantaged’ and ‘disadvantaged’ people. As mentioned above, in this case study, the geographical distribution of the disadvantaged population does not follow any specific patterns.

Figure 3 shows that the main contribution to the global Theil index is given by the *within* component (note that the scales of the two plots are different), whose trend is similar to that of the global Theil, being progressively higher as toll amount and charging radius increase. This means that the main inequalities in the accessibility can be found within each subgroup, as part of it resides inside the charged area and the remaining part outside.

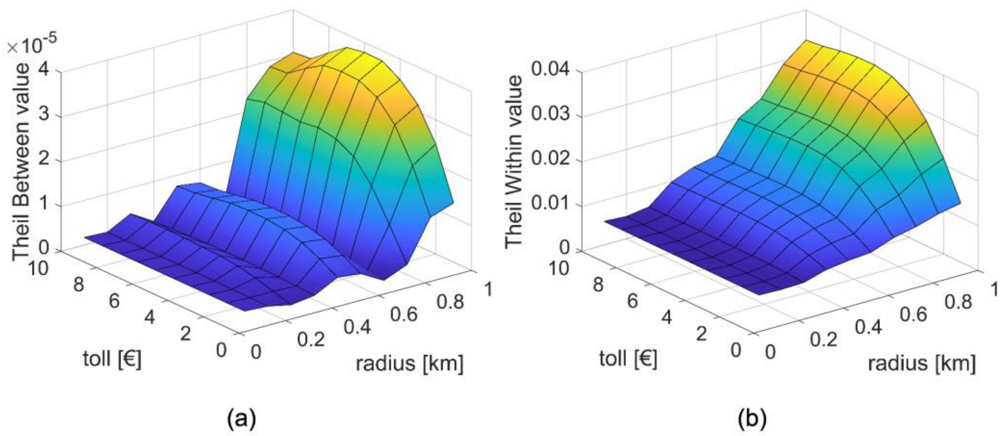

Figure 3. Theil components for the advantaged and disadvantaged subgroups, randomly distributed on the territory: (a) Theil between values; (b) Theil within values.

In the *between* Theil results (Figure 3a), we observe that, while there is still a growing trend when toll and radius rises, there are remarkable fluctuations for certain radius values. For instance, there is a noticeable difference when the radius of the cordon changes from 0.7 km to 0.8 km: a radius larger than 0.7 km seems to exacerbate the inequalities in the accessibility across the two considered segments of the population (advantaged and disadvantaged individuals). To further investigate what happens to these subgroups, one can look at the two components of the *between* Theil, as it can be further decomposed (Figure 4a and 4b).

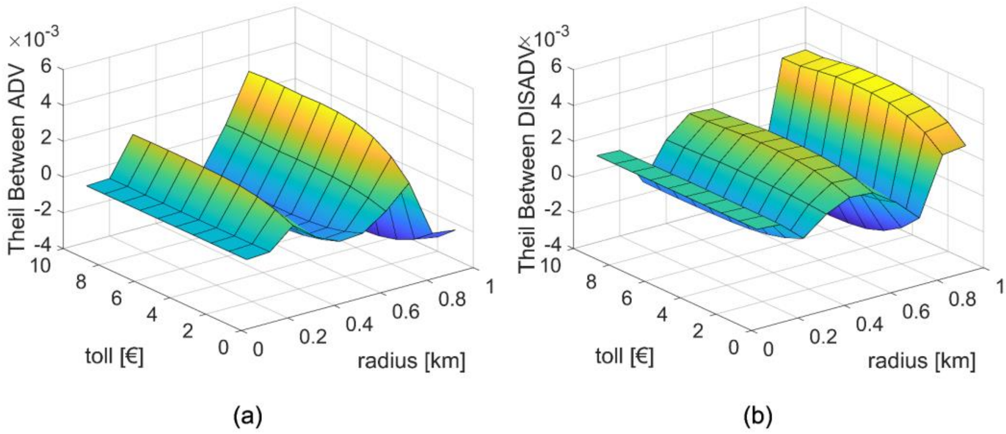

Figure 4. Theil between components: (a) advantaged subgroup (ADV); (b) disadvantaged subgroup (DISADV).

The *between* Theil components can be positive or negative, depending on the ratio between the average accessibility of a subgroup and the overall average accessibility in the study area. In particular, for a 0.8 km cordon radius, we notice a (positive) peak for the advantaged and a drop for the disadvantaged. We can conclude that this particular configuration/radius is the one among the pool of the considered scenarios that more intensifies the differences (inequalities) between the two groups at the expensed of the 'weakest' one.

We can also explore what happens from a spatial perspective, looking at the inequalities in accessibility across the districts/traffic zones of the case study.

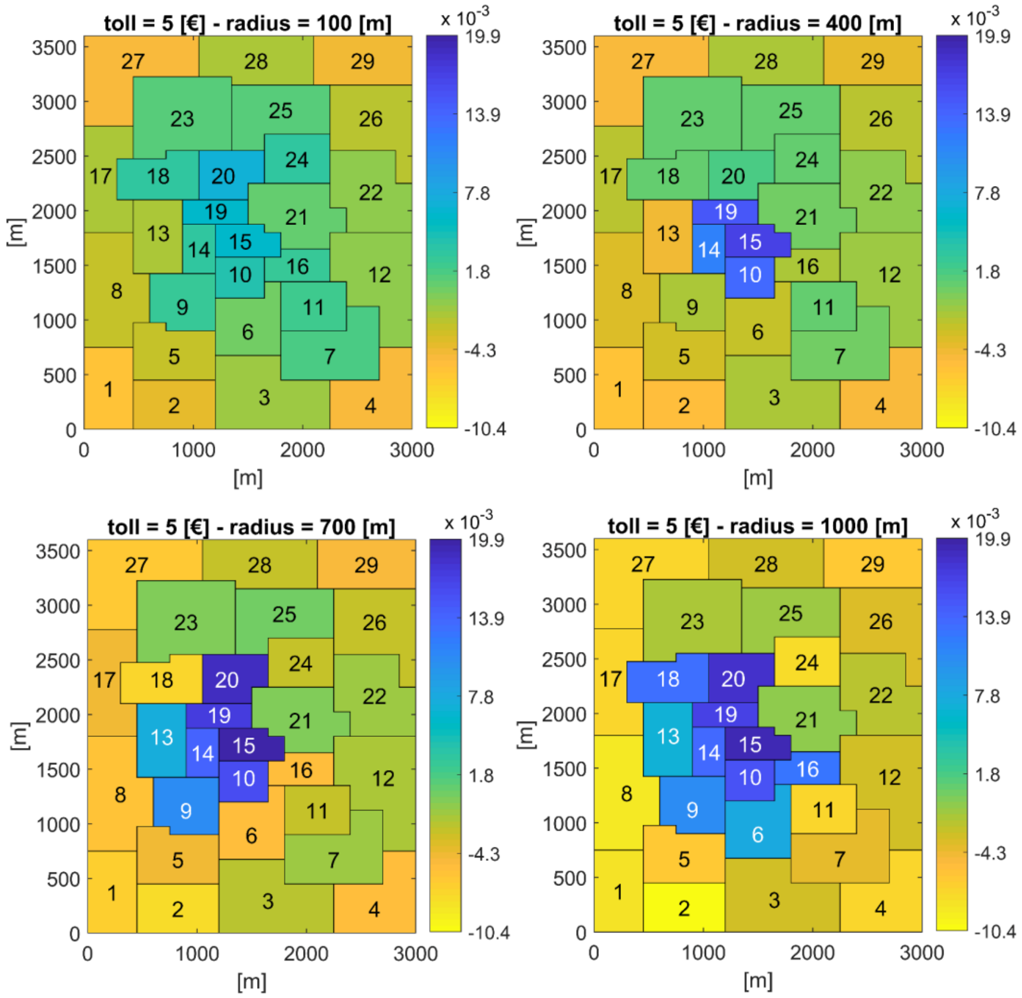

Figure 5. Maps of the Theil between components from a geographical perspective, in four selected scenarios.

Figure 5 maps the between district components of the Theil index in four selected scenarios, with the same toll (5€) and increasing radius of the charged area. Yellow districts (at the bottom of the graded colour scale) are those suffering more from the inequalities in the accessibility, enjoying lower than average per capita accessibility. In Figure 5, it can be seen that as the radius of the cordon grows, the equality in the accessibility of the districts included in the cordoned area rises, while the one of the outsider areas decreases, sharpening the global level of spatial inequalities in the overall territory. Our analysis shows that the worst scenario for any toll amount corresponds to the highest value of the cordon radius.

Downstream of this first analysis, the partial conclusions that we can draw are that the implementation of a congestion pricing scheme, looking at the global accessibility on the network and its associated inequalities, might mainly be done looking at the 'social' components of the Theil between. As a matter of fact, if the trends of the Theil within, and the ones of the spatial Theil between, could be, somehow, foreseen (the inequalities grow as we increase toll and radius), at least it could be possible to avoid those particular scenarios that seem to aggravate the social inequalities of the disadvantaged categories of the population. However, this kind of sensitivity analysis gives the planners the opportunity to have a clearer idea about the results of the pricing policies to implement. A reasonable modal shift can be reached trying at the same time to select one of the optimal scenarios in terms of social and spatial equity, preventing from the implementation of strategies that could encounter more resistance in their acceptance from the network users. It is not a matter of selecting the optimal configuration but giving the decision makers the knowledge that they need to choose the best compromise that helps them achieve their strategical aims.

5.3 Analysis of the accessibility inequalities: disadvantaged districts

The sensitivity analysis above considers a random distribution of disadvantaged population across the territory. This subsection shows what happens if the disadvantaged subgroup is concentrated in some areas of the network. Hereafter we supposed that disadvantaged people reside mainly in zones 8, 9, 13 (Table 3).

Table 3. Different hypothetical distribution of disadvantaged individuals across the zones.

Zone	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***
x_y	24	38	17	25	39	40	16	608	770	53	36	23	607	45	38
Zone	***16***	***17***	***18***	***19***	***20***	***21***	***22***	***23***	***24***	***25***	***26***	***27***	***28***	***29***	
x_y	32	39	47	33	34	5	20	14	44	31	20	49	22	39	

The same sensitivity analysis described in the previous subsection has been repeated for this modified distribution of disadvantaged individuals on the territory. The global Theil index and its social *within* component (i.e. while comparing advantaged and disadvantaged) show a similar trend. On the contrary, substantial differences can be noticed looking at the social Theil *between* values (Figure 6b).

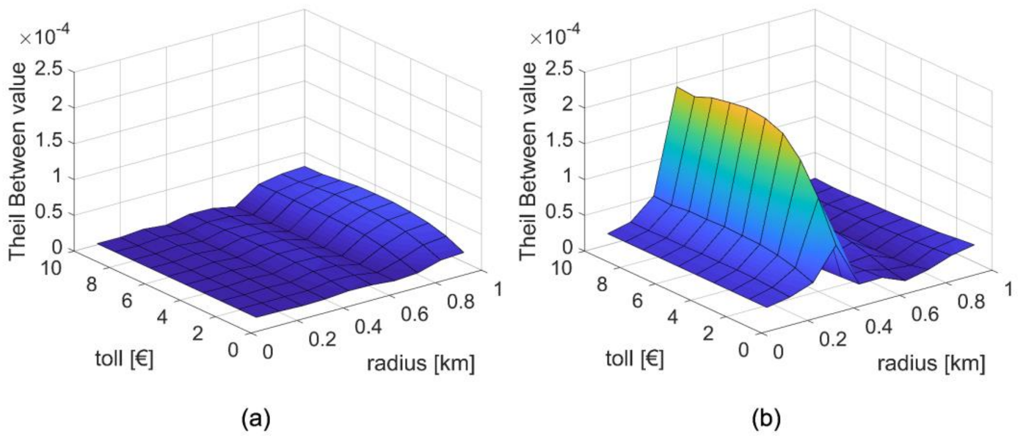

Figure 6. Theil between values: (a) randomly distributed disadvantaged; (b) disadvantaged mainly residing in 3 districts over 29.

For a radius of the charged area equal to 0.4 km, the inequalities between advantaged and disadvantaged individuals increase exponentially. Figure 6a is the same as Figure 3a, but the scale of the z-axis is the same in Figure 6b, to make comparison easier. The inequalities in accessibility with the disadvantaged population concentrated in a few areas (Table 3) are larger than the ones of the first random distribution (Table 1). Table 4 casts light on the reason.

Table 4. Percentage of individuals living within the cordon, while varying disadvantaged distribution across the territory and radius of the charged area.

Randomly distributed disadvantaged (X_y from Table 1)

Radius [km]	*0.1*	*0.2*	*0.3*	*0.4*	*0.5*	*0.6*	*0.7*	*0.8*	*0.9*	*1*
dis/dis_tot [%]	0.0	5.5	7.7	25.1	28.3	34.3	38.3	49.4	58.8	58.8
adv/adv_tot [%]	0.0	5.3	13.9	23.8	30.1	34.1	41.0	44.4	55.2	55.2

Disadvantaged mainly residing in 3 districts over 29 (X_y from Table 3)

Radius [km]	*0.1*	*0.2*	*0.3*	*0.4*	*0.5*	*0.6*	*0.7*	*0.8*	*0.9*	*1*
dis/dis_tot [%]	0.0	1.6	3.0	6.0	27.6	55.1	56.3	57.4	60.5	60.5
adv/adv_tot [%]	0.0	5.8	13.1	26.2	29.8	31.8	38.4	44.6	55.8	55.8

The table shows the percentage of individuals belonging to each subgroup and living within the cordon in relation to the total number of individuals belonging to the same subgroup for different values of cordon radius. The random distribution (x_y in Table 1) does not generate large imbalances between the percentages of advantaged and disadvantaged individuals living inside the cordon. In particular, an almost perfect balance is achieved for a radius of 0.6-0.7 km, corresponding to *between* Theil values close to zero. Then the gap between the two percentages starts to rise again (49.4% - 44.4% = 5%) for a radius of 0.8 km, and so does the *between* component.

In the second distribution (x_y in Table 3), disadvantaged mainly reside in 3 districts, situated between the centre and the periphery of the study area. For a cordon radius of 0.4 km, only 6% of disadvantaged people live within the cordon, i.e. in the areas with greater average accessibility: a low percentage, if we consider that the 26.2% of the advantaged individual resides inside it. This aggravates the differences between social groups, revealing a peak of inequities for that radius (Figure 6b). As the radius increases, a larger share of disadvantaged individuals is included in the charged area, and the balance between the two groups is restored (27.6% comparable to 29.8%). Similar considerations, even if less evident, could be applied to a radius of 0.6 km / 0.7 km, where a further (smaller) peak can be observed.

Note that the spatial equity between districts (Figure 5) remains unchanged for each pricing scenario, as the different distribution of disadvantaged (while the total population of each district stays the same) does not affect the inequalities in accessibility across different geographical areas.

We can conclude that the study of peaks and drops of the Theil between component, together with the modal shift to achieve (and, in a broader context, the expected pricing strategy revenues), could give the policymakers recommendations about the radius of the charged area and the amount of the toll to select.

6. Policy implications and concluding remarks

The paper brings forward a method to analyse the inequalities in the distribution of the multimodal accessibility following the implementation of a cordon-based charging scheme. To this aim, we propose the use of the Theil index, whose mathematical properties allow a detailed analysis of access distributional issues across population groups and geographical area. Our method can help planners implement more equitable strategies, thus achieving a fundamental goal of contemporary urban policies and increasing the public acceptance of the traditionally unpopular tolling measures. Our study can be easily extended to analyse any mobility measure generating spatial or social inequalities, among different population subgroups.

We have illustrated the method with an application to a mock urban area served by private cars and public transport, considering the presence of two categories of residents, which we generically call ‘advantaged’ and ‘disadvantaged’. We have examined two scenarios: in one the disadvantaged population is randomly spread in the urban area, in the other it is concentrated in few districts. The example shows that the method captures the fundamental dynamics triggered by the implementation of the charge. In particular, inequalities generally increase when the charge is levied, because only some travellers have to pay for it. The main contribution to inequalities is given by the fact that not all people belonging to the same group have to pay the charge. The differences between the two groups of residents are less relevant in absolute terms. However, they provide useful indications on less inequitable schemes because the inequalities between groups do not vary uniformly with the cordon radius. The effect of the cordon radius on the between groups inequality is more evident in the scenario where the disadvantaged population is concentrated in some zones.

Given the capacity of the global Theil index and of its components to provide detailed information on the distribution of the inequalities, their use in the definition of pricing strategies can increase the fairness of the adopted strategy. In particular, Theil indexes could be included in the objective function of an optimisation problem or be used to impose constraints limiting the inequalities generated by the toll.

Further research should consider the formulation of optimisation problems considering the Theil index, as well as explorations of the validity of the index in different types of transport problems (for instance, in location problems).

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