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Using connectivity for measuring equity in transit provision

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ABSTRACT

This study proposes the assessment of equity in transit provision by using transit connectivity as a comprehensive impedance measure. Transit connectivity considers in-vehicle time, access/egress times, waiting time, service reliability, frequency, and 'seamless' transfers along multi-modal paths. In addition, transit connectivity weighs the impedance components according to their relative importance to travelers. The assessment of equity was performed for the multi-modal transit system in the Greater Copenhagen Area, renowned for its transit-oriented finger-plan. The assessment method used a GIS representation of the network (i.e., service lines, timetables, metro stations, train stations, and bus stops), and transit assignment results (i.e., level-of-service times, passenger flows). The assessment method proved effective in calculating location-based and potential-accessibility measures and Gini coefficients of inequality in the Greater Copenhagen Area. Results show that the transit-oriented development contributes to spatial equity with high connectivity in densely populated zones, vertical equity with comparable connectivity in high income and low income zones, inter-generational equity with good connectivity provision for students to higher-education and job opportunities. Also, results show that the north-west 'finger' is less equitable with lower connectivity for low population density and lower connectivity to higher-education opportunities regardless of the high number of students.

1. Introduction

The last decades are witnessing a slow but steady paradigm shift from planning 'mass transit' to considering equity and social inclusion as an integral part of the transit planning process. While equity and social inclusion have been initially discussed with respect to fare policies, concessionary fares, and transit subsidies, the perspective has been widened to include population groups with mobility limitations (Ferguson et al., 2012). Most recently, the need for systematically incorporating spatial, temporal and socioeconomic distributional effects in transport decision-making has been discussed (Jones and Lucas, 2012).

The interest in considering equity and social inclusion was first manifested during the 1990's by discussing the need to integrate equity as a policy goal in transport provision (Masser et al., 1992; Gudmundsson and Höjer, 1996). Since the beginning of this millennium, this interest is reflected in the nascence of three main research streams. The first stream describes links between transit provision, time-poverty, social exclusion, and well-being, for both the general (Currie and Delbosc, 2010), disabled (Lubin and Deka, 2012), female (Matas et al., 2010), and low-income (Cebollada, 2009; Lucas, 2011) population. The second stream proposes conceptual frameworks to incorporate equity assessment within transport project appraisal (Martens, 2011; Martens et al., 2012; Thomopoulos and Grant-Muller, 2013). The third stream focuses on integrating equity impact assessment in transit planning and transit appraisal (Ferguson et al., 2012; Monzón et al., 2013). The current study pertains to this third stream.

Equity assessment is the connecting thread across the three lines of research and closely relates to accessibility measurement. Equity is broadly defined as the level of fairness in the distribution of benefits. Transport equity is generally categorized as horizontal equity, concerning the fairness in the distribution of impacts between individuals and groups considered equal in ability and need, and vertical equity, concerning the equality in the distribution of impacts between individuals and groups that differ in abilities and needs (Litman, 2002). Accessibility is broadly defined as the ability and ease of reaching activities, opportunities, services and goods, and accessibility gaps are defined as the differences in accessibility across geographical areas, population groups, and time. These accessibility gaps serve as indicators for identifying spatial, vertical, temporal, and inter-generational inequities (Martens et al., 2012). The definitions of accessibility and the

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classification of infrastructure-based, location-based, gravity-based, person-based and utility-based accessibility measures are extensively reviewed by Geurs and van Wee (2004).

In the transit context, equity assessment often relies on infrastructure-based measures that typically include calculating the population within distance bands from stops by service type, the number of stops by census tract or traffic zone, and the distance to the nearest stop by non-motorized modes. Infrastructure-based measures can be weighted by service capacity and frequency (Delbosc and Currie, 2011; Jaramillo et al., 2012), but their main disadvantage is that they measure the accessibility to the transit system rather than between origins and destinations. For this reason, infrastructure-based measures are typically combined with location-based measures, which consider the impedance between origins and destinations, and potential-accessibility measure, which consider the joint effect of impedance and zone attractivity. Recently, spatial equity (Delmelle and Casas, 2012; Mavoa et al., 2012; Mamun et al., 2013; Monzón et al., 2013), vertical equity (Bocarejo and Oviedo, 2012; Foth et al., 2013) and inter-generational equity (Foth et al., 2013) in transit provision were assessed via potential-accessibility measures. The investigated systems were bus rapid transit (BRT) (Bocarejo and Oviedo, 2012; Delmelle and Casas, 2012), buses (Mavoa et al., 2012; Foth et al., 2013; Mamun et al., 2013; Welch and Mishra, 2013), trains (Mavoa et al., 2012; Foth et al., 2013; Monzón et al., 2013; Welch and Mishra, 2013), and ferries (Mavoa et al., 2012). The impedance measure between origin and destination zones was the travel time calculated from commercial speeds for BRT and trains (Bocarejo and Oviedo, 2012; Delmelle and Casas, 2012; Monzón et al., 2013), and official schedules for buses (Mavoa et al., 2012; Foth et al., 2013; Mamun et al., 2013). The travel time components mostly used for the analysis were in-vehicle time, access/egress time and waiting time, while transfer times were seldom used (Foth et al., 2013; Monzón et al., 2013). These studies presented severe limitations in focusing mainly on travel time, disregarding the different preferences for travel time components, ignoring the probabilistic nature of path choice, overlooking travel time reliability, and calculating equity measures at levels other than spatial.

This study proposes the assessment of equity in transit provision by using transit connectivity as a comprehensive impedance measure, calculating location-based and potential-accessibility measures based on this measure, and computing a Gini coefficient that provides an equity measurement. The proposed assessment method allows overcoming severe limitations of previously applied methods based on accessibility measures. Firstly, the proposed method measures equity while shifting the focus from travel time to a comprehensive measure of in-vehicle time, passenger discomfort associated with waiting, transfer and access/egress times, service reliability and frequency, and "seamless" transfers along multi-modal paths with specified travel demand. Secondly, the proposed method evaluates equity while accounting for differences in the perceived discomfort of passengers for the different time components (Raveau et al., 2011; Anderson et al., 2013). Thirdly, the proposed method assesses equity while considering time variability given the increasingly recognized importance of travel time reliability for passengers as a key objective in transit operations (Ceder and Teh, 2010; Carrasco, 2012). Fourthly, the proposed method evaluates equity while recognizing that in multi-modal transit systems there exist numerous options per origin–destination pair as transit path choice is probabilistic (Raveau et al., 2011; Anderson et al., 2013). Lastly, the proposed method calculates equity while computing a Gini coefficient that allows for considering different levels of equity and different areas of the public transport system with the aim of suggesting possible locations for intervention.

This study applies the proposed method to the multi-modal transit system in the Greater Copenhagen Area (GCA), renowned for its transit-oriented finger-plan for urban development (for an extensive review, see Knowls, 2012). The data consisted of the GIS representation of the multi-modal network including metro, trains, and buses, and detailing service lines, timetables, and stations. Origin–destination travel demand matrices provided information about the current use of the network, and estimates regarding the importance of the travel time components were obtained from the Danish National Transport Model (LandsTrafik-Model, LTM). Zone level data were available regarding zone size, population and socioeconomic characteristics. Transit connectivity was calculated for each origin–destination pair by modifying the algorithm proposed by Ceder (2007), which was previously applied to simplified bus (Ceder et al., 2009; Ceder and Teh, 2010) and water transport networks (Ceder and Varghese, 2011), in order to accommodate multiple paths per origin–destination pair in the complex multi-modal network. Notably, the current study is the first to apply transit connectivity to a large-scale GIS-based metropolitan size network. Location-based and potential-accessibility measures were calculated from the transit connectivity for the zones within the GCA, and maps of their distributions were compared to the maps of the distributions of population characteristics to provide visual comparison of possible gaps in connectivity and hence assess equity. The assessment concerned spatial equity (i.e., fairness with respect to the spatial distribution of opportunities), vertical equity (i.e., equality with regard to groups with different socioeconomic characteristics), and intergenerational equity (i.e., fairness in relation to younger generations having opportunities for reaching equality in the future with respect to the current adult generations). Gini coefficients were computed for the entire study area as well as for sub-areas in the transit-oriented finger-plan to provide a measure of the gaps in equity and suggest possible areas for intervention.

The paper is structured as follows. Section 2 presents the methodology applied in this study by providing details about transit connectivity, location-based and potential-accessibility measures. Then, Section 3 introduces the case study with the description of the study area, the transit network and the multi-modal transit services. Last, Section 4 presents the results and Section 5 draws the conclusions of the study.

2. Methodology

The methodology for measuring equity in transit provision consists of three stages: (i) measure of transit connectivity, (ii) calculation of location-based and potential-accessibility measures, and (iii) computation of Gini coefficients per measure and per area.

2.1. Transit connectivity

The measure of transit connectivity derives from the modification of the algorithm proposed by Ceder (2007) to accommodate multiple paths per origin–destination pair in the complex multi-modal network. The description of the algorithm follows, while the details of its mathematical formulation are provided in the Appendix.

The measure of transit connectivity requires the input of a multi-modal transit network represented by a directed graph $G(V,A)$ and a zone system. The set V of vertices contains (i) zone centroids and (ii) transit stops, while the set A of arcs contains (i) connectors from the centroids to the stops, (ii) transit line arcs between the stops, and (iii) transfer connectors between lines at the stops. Moreover, the measure requires the input of a schedule-based transit assignment that loads the demand for transit between origin zones O_i and destination zones D_j (see, e.g., Sheffi, 1985; Nielsen, 2000). The transit assignment produces level-of-service variables