Using Connectivity for Measuring Equity in Transit Provision

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ABSTRACT

This study proposes transit connectivity as a comprehensive impedance measure for equity assessment within transit planning and evaluation processes. Transit connectivity considers travel time, access/egress times, waiting time, service reliability, frequency, and ‘seamless’ transfers along multimodal paths. In addition, transit connectivity considers the relative importance of impedance components. The method is applied to the multimodal transit system in the Greater Copenhagen Area, renowned for its transit-oriented finger-plan. The GIS representation of the network includes service lines, timetables, and stations of metro, trains, and buses. The algorithm considers multiple paths between origin-destination pairs and proves effective in measuring origin and destination connectivity in the zones of the Greater Copenhagen Area in relation to their socioeconomic characteristics. Results show (i) high connectivity to densely populated zones with lower values in the eastern ‘finger’, (ii) connectivity cavities that are mainly spatial but also income related, (iii) high connectivity of employees to the locus of knowledge, and (iv) high connectivity of students to higher-education institutions and employment centers with the exception of the eastern ‘finger’.
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 (1). Most recently, the need for systematically incorporating spatial, temporal and socioeconomic distributional effects in transport decision-making has been discussed (2).

The interest in considering equity and social inclusion was first manifested during the 90’s by discussing the need to integrate equity as a policy goal in transport provision (3, 4). 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 (5), disabled (6), female (7), and low-income (8, 9) population. The second stream proposes conceptual frameworks to incorporate equity assessment within transport project appraisals (10, 11, 12). The third stream focuses on integrating equity impact assessment in transit planning and transit appraisal (1, 13). The current study pertains to this third stream.

Equity assessment is the connecting thread across the three research and closely relates to accessibility measurement. 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 (11). The definitions of accessibility and the classification of infrastructure-based, location-based, gravity-based, person-based and utility-based accessibility measures are comprehensively reviewed by Geurs and van Wee (14).

In the transit context, infrastructure-based measures typically include measuring 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 (15, 16), 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 transport and land use by combining impedance and zone attractivity. Potential-accessibility measures were recently employed to evaluate transit provision in terms of spatial (13, 17, 18, 19), socioeconomic (20, 21) and inter-generational (21) equity. The investigated systems were bus rapid transit (BRT) (17, 20), buses (18, 19, 21) and high-speed trains (13), and the impedance measure between origin and destination zones was the travel time calculated from commercial speeds for BRT and trains (13, 17, 20) and official schedules for buses (18, 19, 21). 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 (13, 21). The aforementioned studies have four limitations. Firstly, the connection between origins and destinations considered a single transit path, while in complex multi-modal transit systems there exists more than one option per origin-destination pair as transit path choice is probabilistic (see, e.g., 22). Secondly, travel time was calculated deterministically without variability, although the importance of travel time reliability for passengers is increasingly recognized as a key objective in transit operations (23, 24). Thirdly, travel time was summed
over its components to provide a door-to-door time, while there exist importance weights for the different travel time components according to differences in the perceived discomfort of the passengers (25). Lastly, transfer times were considered by some studies, but transfers are associated with additional inconvenience and their number should also be considered (25).

This study proposes to use transit connectivity as a comprehensive impedance measure for the calculation of both location-based and potential-accessibility measures that relate to equity assessment within transit planning and evaluation processes. Transit connectivity was proposed by Ceder (25) and applied to bus (23, 26) and water transport systems (27). While previous accessibility measures focused on travel time, transit connectivity considers travel time, passenger discomfort associated with waiting, transfer and access/egress times, service reliability and attractiveness, frequency, and “seamless” transfers along multimodal paths with specified travel demand as part of the door-to-door passenger chain. Thus, transit connectivity is free of the aforementioned four limitations and offers a deep and comprehensive understanding of accessibility gaps as equity indicators. In addition, for each origin-destination pair, transit connectivity is calculated for a set of multiple and feasible transit paths including the three shortest paths and the three most popular paths (i.e., the paths with the maximum demand) in order to account for the probabilistic nature of transit path choice.

This study focuses on the multimodal transit system in the Greater Copenhagen Area (GCA), renowned for its transit-oriented finger-plan for urban development (for an extensive review, see 28). The data consisted of the GIS representation of the multimodal 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 (LandsTrafikModel, LTM). Zone level data were available regarding zone size, population and socioeconomic characteristics including employment status, age and income. Transit connectivity was calculated for each origin-destination pair and distributions of origin and destination connectivity were compared to the distributions of socioeconomic population characteristics to assess spatial and vertical equity. Notably, the current study is the first to apply the connectivity measure to a large-scale GIS-based metropolitan size network.

The paper is structured as follows. The next section presents the methodology applied in this study by providing details about transit connectivity, location-based and potential-accessibility measures. Then, the case study is introduced with the description of the study area, the transit network and the multimodal transit services. Last, results are presented and discussed, and conclusions are drawn.

**METHODOLOGY**

The methodology for measuring equity in transit provision consists of two stages: (i) calculation of transit connectivity, and (ii) computation of aggregate connectivity for equity assessment.

**Transit Path Connectivity**

The calculation of transit connectivity follows the methodology proposed by Ceder (25).

Consider a transit network represented by a directed graph \( G(V,A) \), where \( V \) is the set of vertices \( v \) containing (i) zone centroids and (ii) transit stops, and \( A \) is the set of arcs \( a \)
containing (i) connectors from the centroids to the stops, (ii) transit line arcs between the stops, and (iii) transfer connectors between lines at the stops. Consider the following notation:

- \( O = \{O_i\} \) is the set of origins \( O_i \);
- \( D = \{D_j\} \) is the set of destinations \( D_j \);
- \( P_{ij} = \{p_{ij}\} \) is the set of multimodal paths \( p_{ij} \) connecting origin \( O_i \) and destination \( D_j \);
- \( M_p = \{m\} \) is the set of transit modes \( m \) included in path \( p_{ij} \);
- \( E = \{e^q\} \) is a set of quantitative and qualitative attributes \( e^q \) suitable for calculating transit connectivity;
- \( \omega_{eq} \) is the weight for each attribute \( e^q \);
- \( e^q_a \) is the value of attribute \( e^q \) for arc \( a \);
- \( e^q_p \) is the value of attribute \( e^q \) for path \( p \), equal to the sum of \( e^q_a \) over the arcs composing path \( p \);
- \( c^q_p \) is the connectivity measure \( c^q \) relative to attribute \( e^q \) for path \( p \);

The attributes \( e^q \) consist of 8 quantitative attributes \((t=1,\ldots,8)\) and 3 qualitative attributes \((l=9,\ldots,11)\) that are computed for paths \( p_{ij} \) within the set \( P_{ij} \). The quantitative attributes are computed according to assignment results, but could also be calculated according to scheduled services \((25, 26)\). The qualitative attributes are computed according to proxies, but could also be calculated according to passenger surveys \((25, 26)\). Both quantitative and qualitative attributes are weighted to capture heterogeneity in the preferences for modes and paths across passengers and also for the same passenger across situations. The weights \( \omega_{eq} \) are based on assignment results, but could also be based on passenger surveys \((25, 26)\).

Given these definitions, the following algorithm is defined for the calculation of transit connectivity in the transit network \( G(V,A) \) for a given time window (e.g., peak-hour):

- **Step 0.** Define the set \( O \) of origins and the set \( D \) of destinations, list the \( N \) \( O_i-D_j \) pairs, and consider the following arc attributes \( e^q_a \):
  - in-vehicle time \( t_{ta,m} \) for mode \( m \) on arc \( a \);
  - walking time \( t_{la,cn} \) on arc \( a \) that is a connector \( cn \) between an origin and a stop;
  - walking time \( t_{la,ch} \) on arc \( a \) that is a transfer arc \( ch \) between stops;
  - waiting time \( t_{wa,v} \) at the initial stop \( v \) of arc \( a \);
  - scheduled headway \( t_{ha,v} \) at the initial stop \( v \) of arc \( a \);
  - transfer time \( t_{ra,ch} \) for any mode on arc \( a \) that is a transfer arc \( ch \) between stops;
  - transfer time \( t_{ra,ch,m} \) for mode \( m \) on arc \( a \) that is a transfer arc \( ch \) between stops.

- **Step 1.** For \( O_i-D_j \) pair \( n \), create the set \( P_{ij} \) of multimodal paths \( p_{ij} \):
  - find \( k \)-shortest paths by minimizing path travel time (i.e., considering travel time as impedance on arc \( a \)), and add them to the set \( P_{ij} \);
  - find \( k \)-shortest paths by maximizing path demand (i.e., considering average number of passengers as impedance on arc \( a \)), and add them to the set \( P_{ij} \).
Step 2. For each arc attribute $e^a_a$, normalize its scale over the $A$ arcs to make the connectivity measures comparable (25, 26):

$$\left\|e^a_a\right\| = \frac{e^a_a}{\sum_{a \in A} e^a_a} \quad \forall a \in A$$

Step 3. For $O_i-D_j$ pair $n$ and each path $p$ in the set $P_{ij}$ composed by $2k$ paths, calculate the following path attributes from the normalized arc attributes (the normalization notation and the origin-destination notation in the path are dropped to improve readability):

- in-vehicle time $tt_{p,m} = \sum_a e^a_a(t_{ta,m})$ for mode $m$ on path $p$;
- walking time $tl_{p,cn}$ on connector $cn$ between $O_i$ and boarding stop of path $p$;
- walking time $tl_{p,ch}$ on transfer arcs $ch$ between stops of path $p$;
- walking time $t_p = tl_{p,cn} + tl_{p,ch}$;
- waiting time $tw_p$ at the boarding stop of path $p$;
- scheduled headway $th_p$ at the boarding stop of path $p$;
- transfer time $tr_{p,ch}$ for any mode on transfer arcs $ch$ of the path $p$;
- transfer time $tr_{p,ch,m}$ for mode $m$ on transfer arcs $ch$ of the path $p$;
- number of transfers $chp_v$ on path $p$.

Step 4. For $O_i-D_j$ pair $n$, calculate the values $e^g_p$ of the following attributes:

- average walking time:
  $$e^1_p = \frac{1}{2k} \sum_{p \in P_{ij}} tl_{p} = \frac{1}{2k} \sum_{p \in P_{ij}} \left( \sum_{cn} tl_{p,cn} + \sum_{ch} tl_{p,ch} \right) \quad \forall p \in P_{ij}$$  
  
- variance of walking time:
  $$e^2_p = \frac{1}{2k} \sum_{p \in P_{ij}} tl_{p} - e^1_p \quad \forall p \in P_{ij}$$

- average waiting time:
  $$e^3_p = \frac{1}{2k} \sum_{p \in P_{ij}} tw_{p} = \frac{1}{2k} \sum_{p \in P_{ij}} \left[ \frac{1}{2} th_p \left( 1 + \frac{\text{var}(th_p)}{th_p^2} \right) \right] \quad \forall p \in P_{ij}$$

- variance of waiting time:
  $$e^4_p = \frac{1}{2k} \sum_{p \in P_{ij}} tw_{p} - e^3_p \quad \forall p \in P_{ij}$$

- average in-vehicle time:
  $$e^5_p = \frac{1}{2k} \sum_{p \in P_{ij}} \left( \sum_{m \in M_p} tt_{p,m} \right) \quad \forall p \in P_{ij}$$
○ variance of in-vehicle time:
\[ e^6_p = \frac{1}{2k} \sum_{p \in P_{ij}} \left[ \left( \sum_{m \in M_p} t_{t_{p,m}} \right) - e^5_p \right]^2 \quad \forall p \in P_{ij} \] (7)

○ average scheduled headway:
\[ e^7_p = \frac{1}{2k} \sum_{p \in P_{ij}} th_p \quad \forall p \in P_{ij} \] (8)

○ variance of scheduled headway:
\[ e^8_p = \frac{1}{2k} \sum_{p \in P_{ij}} th_p - e^7_p^2 \quad \forall p \in P_{ij} \] (9)

○ number of transfers:
\[ e^9_p = \sum_v ch^v_p \quad \forall p \in P_{ij} \] (10)

○ smoothness of transfer across modes:
\[ e^{10}_p = \sum_{ch} t^{ch}_{p} \quad \forall p \in P_{ij} \] (11)

○ smoothness of transfer within modes:
\[ e^{11}_p = \sum_{ch} t^{ch,m}_{p} \quad \forall p \in P_{ij} \] (12)

– Step 5. For \( O_i-D_j \) pair \( n \), calculate the path connectivity:
○ connectivity \( c_p \) for path \( p \):
\[ c_p = \sum_{e \in E} \omega_{e^s} \cdot e^i_p \quad \forall p \in P_{ij} \] (13)

○ connectivity \( C_{ij} \) for \( O_i-D_j \) pair \( n \):
\[ C_{ij} = \sum_{p \in P_{ij}} c_p = \sum_{p \in P_{ij}} \left[ \sum_{e \in E} \omega_{e^s} \cdot e^i_p \right] \] (14)

– Step 6. Update \( n=n+1 \) and return to step 2 for another \( O_i-D_j \) pair \( n \), otherwise stop.

Aggregate Connectivity for Equity Assessment

The calculation of transit connectivity at the path, origin and destination level allows computing location-based and potential-accessibility measures.

Location-based measures relate to the calculation of transit connectivity at the zone level. Consider the set \( P_{Oi} = \{ P_i \} \) of multimodal paths \( p_{ij} \) from origin \( O_i \) and the set \( P_{Dj} = \{ P_j \} \) of multimodal paths \( p_{ij} \) to destination \( D_j \). Having computed the connectivity \( c_p \) of each path \( p \), it is possible to calculate the connectivity \( C_i \) for each zone as the origin of transit trips and the connectivity \( C_j \) for each zone as the destination of transit trips:
The origin connectivity $C_i$ measures the possibility of each zone $i$ to reach every other zone in the study area, and hence the prospect for the population of zone $i$ to reach opportunities (e.g., jobs, universities, hospitals) in every other zone. The destination connectivity $C_j$ measures the possibility of each zone $j$ to be reached from every other zone in the study area, and hence the prospect of the opportunities in zone $j$ to be accessible by the population of every other zone. Notably, the connectivity $C_{ij}$ for each $O_i$-$D_j$ pair expresses the possibility of the population in zone $i$ to reach the opportunities in zone $j$. When comparing origin and destination connectivity across zones, a classification of the zones according to connectivity distribution percentiles provides insight into the spatial equity in the study area. When adding to the comparison a layer of socioeconomic characteristics of each zone, the comparison of the connectivity distribution percentiles with the socioeconomic characteristic percentiles provides insight into the vertical equity in the study area.

Potential-accessibility measures relate to the calculation of the connectivity at the zone level and the size of the zone. It is possible to calculate the public transport provision $PTP_i$ of each zone $i$ by modifying a formulation that offers appropriate balance between complexity and interpretability (see, e.g., 13):

$$PTP_i = \frac{\sum_{D_j \in D} P_{gi}}{\sum_{D_j \in D} \left( \sum_{p \in P_{h_i}} \left( \sum_{e' \in E} \omega_{e'} \cdot e_p \right) \right)}$$

The public transport provision $PTP_i$ weighs the origin connectivity $C_i$ according to the size that may be expressed as a portion $P_{gi}$ of the population (e.g., number of jobs, number of students), in order to express the facility to reach a locus of opportunity. When comparing $PTP_i$ across zones and adding a socioeconomic layer, especially if relating specific population groups to specific opportunities (e.g., students and universities), the analysis provides valuable insight into the vertical equity in the study area.

This study applies the described methodology for connectivity calculation in combination with GIS resources in order to produce maps that allow conveying the relevant information in an intuitive visual representation of the connectivity distributions and the socioeconomic characteristic distributions across zones, thus representing spatial and vertical equity in an intelligible and easily accessible manner.

**CASE STUDY**

This study focuses on the GCA, which comprises 18 municipalities extending for about 3000 sq.km. with a population of about 2 million people. The planning and the development of the transit system in the GCA follows the finger-plan directives (see 28), which indicate five cities (Køge, Roskilde, Frederikssund, Hillerød and Helsingør) as the direction from Copenhagen for the fingers to be served by transit and road connections.

The transit network of the GCA consists of seven major modes: (i) metro, (ii) local trains, (iii) suburban trains (S-trains), (iv) regional and intercity trains (Reg-trains and IC-
trains), (v) regular buses, (vi) high-frequency buses (A-buses), and (vii) suburban and express buses (S-buses and E-buses). The metro serves central Copenhagen and the airport. The Reg- and IC-trains lead north and west of Copenhagen, while the S-trains follow the radial finger lines from central Copenhagen to the mentioned five cities. E-buses and S-buses serve the S-train stations (primarily in rings), A-buses operate in central Copenhagen, and the remaining buses run in Copenhagen, the suburbs and the rural areas at a lower frequency. Figure 1 provides an overview of the transit network in the GCA with the representation of train lines and metro lines over the dense background of the bus lines.

The GIS representation of the transit network consists of 264 traffic zones from the LTM, 2400 connectors, 222 transfer arcs, 34,752 transit line arcs, 22 metro stations, 89 train stations, and 1181 bus stations. Accordingly, the network $G(V,A)$ for this study consists of 1292 vertices and 37,374 arcs, with attributes $e_{a}^{j}$ for the morning peak-hours (7am-9am) being digitized and entered into Matlab codes for k-shortest path calculations and connectivity computations.

The LTM was the main source of information. Firstly, arc attributes $e_{a}^{j}$ were retrieved from the LTM transit assignment that produced the values for in-vehicle times, waiting times, walking times, headways and passenger flows on the arcs. Secondly, weights $\omega_{e}$ were retrieved from the calibration of the traffic assignment to represent heterogeneity in mode preference and time perception: metro and S-trains were preferred to trains and buses, and walking and waiting times were perceived more sensibly than in-vehicle times. Thirdly, demographic (e.g., population, density, age groups) and socioeconomic (e.g., income, employment) attributes were reported for the 264 origin zones $O_{i}$ and destination zones $D_{j}$.

Given the network $G(V,A)$, arc attributes $e_{a}^{j}$, weights $\omega_{e}$ and attributes of origins $O_{i}$ and destinations $D_{j}$, the described algorithm was applied and the quintiles of the distributions of origin and destination connectivity were calculated for their graphical representation. It should be noted that the original algorithm (25) considered also (i) the availability of easy-to-observe and easy-to-use information channels and (ii) the interagency connectivity satisfaction, which were not considered in this study. The former was assumed to be equally distributed over the GCA, as timetables are reported at every transit station, real-time electronic information is largely available throughout the metropolitan area and smartphone applications are widely used. The latter was assumed not to be relevant, as the GCA transit system is franchised and a planning agency (MOVIA) coordinates the fare collection and the strategic and tactical planning across operators, thus fostering the smoothness of the inter-operator connectivity throughout the study area.
RESULTS

The connectivity was calculated for the morning peak-hour (7am-9am), and hence results focus on mandatory activities (i.e., work and higher-education) for equity assessment. In particular the assessment concerns (i) spatial and vertical equity with respect to employment opportunities, (ii) spatial equity with respect to professional networking and collaboration, (iii) inter-generational equity with respect to higher-education opportunities, and (iv) inter-generational equity with respect to knowledge-based employment opportunities.

Connectivity to Employment Opportunities

The importance of transit connectivity to employment opportunities as a fundamental pillar of equity is related to the need to increase social inclusion in the labor market, provide opportunities for revenue increases, and reduce time-poverty.

Figure 1 presents the distributions of origin and destination connectivity of the GCA zones alongside the distributions of their population density, average income and number of jobs. The origin connectivity is presented also as a graph of connectivity values alongside the corresponding map, in order to provide an example of the construction of the maps from the calculated connectivity values. The values in the graph are presented at an aggregate zone level because of the large number of zones in the study area, while the maps are presented at the traffic zone level.
From the origin connectivity perspective, emerges the general advantage of the transit-oriented development in terms of spatial equity. Zones with higher population density in the metropolitan core and along the train lines enjoy better connectivity. Nevertheless, the finger-plan is only partially associated with spatial equity because the same origin connectivity is not observed for all the ‘fingers’. The highest connectivity is along the north-east ‘finger’ to Hillerød and the south-east ‘finger’ to Roskilde, high connectivity is along the ‘finger’ to Helsingør only until the boundary of Greater Copenhagen, and lower connectivity is observed along the east ‘finger’ to Frederikssund and the south ‘finger’ to Køge are in the lowest quintile. The low connectivity along these ‘fingers’ is in conflict with their high population density and is similar to the connectivity of the low density outskirts of the metropolitan area. In terms of vertical equity, while the zones with the highest average income enjoy better connectivity, the zones that are less better-off in terms of connectivity are not much worse-off.
in terms of income. In fact, most of the less connected zones are in the second-best and average income quintiles. Exceptions are the area located between the train lines to Farum and to Roskilde (Nørrebro, Emdrup, Gentofte Ø, Vesterbro), with high population density in the lowest income quintile suffering the worst connectivity, and the area located east of the Roskilde fjord, with low population density in low income having low connectivity.

From the destination connectivity perspective, while most jobs are located in the metropolitan core and along the train lines of the finger-plan, not all enjoy the same connectivity. The metropolitan core and the destinations along the north-east ‘finger’ to Hillerød enjoy the highest level of connectivity, as well as Roskilde and its periphery. The jobs located along the ‘finger’ to Køge also enjoy a relatively high connectivity, while the workplaces along the ‘finger’ to Frederikssund have the lowest connectivity. Considering the high number of jobs in this area, there is a spatial mismatch between the number of jobs and the destination connectivity along the ‘finger’ to Frederikssund, and the mismatch is even more evident in the suburbs near the metropolitan core.

**Connectivity to Professional Networking and Collaboration**

Knowledge accumulation is related to social, economic and job mobility of individuals and firms, which are associated with more equitable societies due to reduced dependency on head-start assets. Knowledge-sharing through intra- and inter-organizational social networks serves as an important channel for tacit knowledge accumulation, a necessary tool for skill development and innovation, and an instrument for alliance formation. Access to tacit knowledge through social networks of peers and colleagues has been shown more valuable to the career advancement of junior and middle employees than explicit knowledge from stand-alone information resources (29). Despite technological advancements in computer-aided communication, personal face-to-face interactions remain highly important in tacit knowledge-sharing among peers and colleagues. Recently, it was found in the Danish pharmaceutical industry that social relations, physical proximity to colleagues and meetings in informal spaces are important enablers of knowledge-sharing (30).

Figure 2 shows the connectivity of employees to the locus of social knowledge, which is calculated as $PTP$ by dividing the number of workers employed in each zone by its connectivity to the other zones as a measure of the potential of work-related meetings with employees in the other zones. The potential is higher for zones with good connectivity and higher number of workers employed in the zone, and the $PTP$ to the locus of social knowledge is presented alongside the number of employees working in each zone.

The figure shows the advantage of the transit-oriented development in the GCA for facilitating connectivity to the locus of social knowledge. Large concentrations of employees work in the metropolitan core and along the train lines, which ensures good connectivity across employees in different employment centers. Nevertheless, the connectivity to the east along the Copenhagen-Taastrup line and between the Copenhagen-Taastrup line and the Copenhagen-Frederikssund line could be improved, considering that the number of employees is in the highest quantile, but the $PTP$ is in the second-best quantile.
Higher-education institutions have an important role in promoting horizontal, vertical and inter-generational equity. Graduates and undergraduates of higher-education institutions have a wider locus of opportunities for employment and higher wages, and thus can improve their economic, societal and geographical mobility.

Despite the availability of virtual learning aids, transit connectivity to higher-education remains an important barrier to the inclusion in academic activities, the ability to use knowledge resources, and the opportunity to network as part of campus life. Among the identified transport problems are transit unavailability, long walking and travel time, delays, and service hours (31).

Figure 3 shows the residential location of students compared to the connectivity to the main university campuses in the GCA. The residential location of students is based on data from the LTM regarding 18-25 year-old residents that are registered as students. The considered universities are the Technical University of Denmark (DTU), Copenhagen University, Roskilde University, Aalborg University, University of Southern Denmark, Copenhagen Business School, IT University of Copenhagen, and Copenhagen School of Fine Arts. While some faculties are located outside the main campuses around the city, the assessment of connectivity was conducted with respect to the main campus as the main academic and administrative service provider. The connectivity from each zone to all the universities was calculated because of university specialization and capacity constraints, and hence measures the locus of opportunities for students in each zone.

Naturally, many of the student concentrations are located in proximity to the main campuses and enjoy a high level of connectivity. Students located in both the southern and northern outskirts of the metropolitan area also enjoy relatively good connectivity to higher-education campuses. The main connectivity cavity is located between the line to Farum and the line to Frederikssund, where a large concentration of students resides in an area of relatively poor connectivity despite its spatial proximity to the city center and the main
An example is Tingbierg Kollegiet, a student accommodation facility with a capacity of 300 rooms for DTU students that is located 15km from DTU and is served by a bus-train-bus combination with a travel time of approximately 45min. In a recent survey conducted among 100 students in Tingbierg Kollegiet, 37% declared to commute by public transport, 58% stated to commute by bicycle, and 94% of the students expressed their interest in establishing a shuttle bus service between the facility and the campus (32).

**Figure 3  Connectivity of students to the main university campuses.**

**Connectivity to Knowledge-Based Employment Opportunities**

Youth employment is a key issue in promoting inter-generational equity. While education is essential to increase youth employment, college graduates experience difficulties in entering a highly competitive labor market due to lack of experience and labor market familiarity. Consequently, they experience longer job searches, lower starting salaries and anxiety in the short-term, and lower living standards, psychological effects and lack of inter-generational solidarity in the long-term. Gaining experience, developing skills and professional networks, and becoming familiar with the labor market through internships in companies strengthen students’ employability upon graduation and facilitate their entrance in the labor market (33). Internships during studies become increasingly important in the highly competitive knowledge-driven labor market and in particular in times of financial austerity (34).

Denmark, the OECD country with the lowest youth unemployment rate, has a dual system combining higher-education and internships. Students are encouraged to participate in internship programs, engage in collaborations with companies, and work 10-20 hours per week in a company relevant to their study area in the advanced stages of their education. Internship programs of about 3-6 months are often embedded within academic curricula and project collaborations with Danish companies are typical parts of B.Sc. and M.Sc. final projects. Working and studying implies alternative commuting to the university and the company, and hence good transit connectivity to the main knowledge-work compounds as potential internship locations is a necessary pre-condition for successfully combining higher-education and internship.
Figure 3 shows the residential location of students alongside the destination connectivity to the main compounds representing a wide range of knowledge-based and business industries in the GCA: the CBD, Ørestad City, Symbion, Brink Business Park, COBIS and Skovlunde business park, CAT Science Park and Scion in the north, Ballerup business park, Måløv business park, and Lautrupgård in the east, and CAT Science Park RSU in the eastern outer ring. The connectivity measures the spatial locus of employment opportunities for students in each zone by calculating the connectivity from each residential zone to all the potential employment compounds.

The figure clearly shows that both students located near the metropolitan core and immediately north and south of the core are well connected to the main employment compounds. Moreover, while zones with high student concentrations enjoy the best connectivity, zones with a low number of students also have reasonably average connectivity. Thus, the transit-oriented development supports inter-generational equity by providing an adequate transport infrastructure to the Danish dual system combining higher-education and internship. The main connectivity cavity is between the line to Farum and the line to Frederikssund, where a large concentration of students resides in an area of relatively poor connectivity despite its spatial proximity to the city center and many employment compounds.

CONCLUSIONS

The last decades have witnessed a steady paradigm shift from planning ‘mass transit’ to considering spatial, vertical and inter-generational equity as an integral part of the transit planning process. This study proposes transit connectivity as a comprehensive impedance measure for equity assessment within transit planning and evaluation processes. Location-based and potential-accessibility measures based on transit connectivity relax the limitations of existing accessibility measures by (i) recognizing the probabilistic nature of transit path choice, (ii) considering travel time reliability, (iii) weighing the various time components, and (iv) considering the number of transfers as an additional burden. The method is applied to the multimodal transit system in the GCA, renowned for its transit-oriented finger-plan.
The analysis focused on the morning peak-hour and hence on the connectivity to employment and higher-education. Equity was assessed in terms of (i) spatial and vertical equity with respect to employment opportunities, (ii) spatial equity with respect to professional networking and collaboration, (iii) inter-generational equity with respect to higher-education opportunities, and (iv) inter-generational equity with respect to knowledge-based employment opportunities.

The transit-oriented development of the finger-plan is generally beneficial because densely populated areas enjoy high origin connectivity, and areas offering high numbers of jobs enjoy high destination connectivity. Nevertheless, the results also show that, despite similarities in the distribution of population and employment along the ‘fingers’, the origin and the destination connectivity along the eastern ‘finger’ to Frederiksund is worse, likely because of the lower frequency of the trains and longer access times to the stations. This result demonstrates the importance of considering a comprehensive measure of location-based connectivity rather than simple infrastructure-based accessibility, as proximity to transit infrastructure does not grasp the complete service evaluation.

In terms of vertical equity, while the zones with the highest average income enjoy better connectivity, the zones that are less better-off in terms of connectivity are not much worse-off in terms of income. Nevertheless, there are exceptions in zones that are highly-populated, have a low average income and have a relatively low connectivity level, albeit their proximity to the metropolitan core. The connectivity cavities associated with these zones were found in all the investigated aspects of the equity assessment.

The transit-oriented development of the finger-plan is beneficial in terms of connectivity to the locus of knowledge as a factor that encourages economic and social mobility. Because most workplaces are located in the metropolitan core and along the train lines, it is relatively easy for employees to conduct meetings with other employees across the metropolitan area. The high origin connectivity to zones with high number of employees relaxes the need for geographical proximity and facilitates face-to-face interactions, which are still an important factor in tacit knowledge-sharing.

The results show high connectivity for the student population to higher-education institutions and the main industrial, science and business compounds, which contribute to inter-generational equity by increasing the employability of university graduates. The high connectivity of students to these facilities is because most of the main university campuses and the considered employment compounds are located in the metropolitan core and along the north-eastern train line to Hillerød, both characterized by a high level of destination connectivity. Nevertheless, a cavity exists in the eastern suburb near the metropolitan core where a large concentration of students suffers low connectivity, and this issue is important since several university dormitories are located in this area.

Overall, the study proves effective in measuring origin and destination connectivity in the zones of the Greater Copenhagen Area, computing location-based and potential-accessibility measures, and evaluating equity of public transport provision in relation to the socioeconomic characteristics of the zones. Notably, while transit connectivity has been previously applied as a transit performance measure, this study is a pioneer work in calculating connectivity in a large-scale metropolitan network consisting of hundreds of zones and thousands of arcs and discussing equity assessment via visual representation of the distributions of connectivity and socioeconomic characteristics of the zones in geographical maps.
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REFERENCES


