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Assessment of large-scale transitions in public transport networks using open timetable data: case of Helsinki metro extension

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ABSTRACT

Transforming a direct radial network to a trunk-feeder system is an often-argued method of large-scale overhaul in public transport networks. In planning such large-scale network overhauls, planners are often facing a dilemma when trying to achieve a careful balance between efficiency and equity, as overhaul might result in an unequal distribution of benefits and burdens for end users. Despite theoretically well-known trade-offs between trunk-branch and trunk-feeder networks, there are limited empirical studies documented from the user perspective, accounting for both travel time and transfers. Conventional methods used in practice, such as cost-benefit analyses, are often lacking the capacity to take into account equity effects. Having in mind the need for drawing lessons from actual overhauls, this research presents the assessment of changes in travel time and number of transfers brought about by the Helsinki metro extension, which involved the transformation of a direct bus network to a metro system with feeder buses. To this end, we develop a methodology for assessment of large-scale public transport network overhauls, building upon the previous development in service-equity assessment methods. Based on the use of open timetable data, the methodology centers on continuous journey calculations between all public transport access points. Thus, this methodology highlights the changes in travel time and transfers that would not be noticed in an aggregate assessment approach. In particular, the methodology reveals the disaggregate effects of the network overhaul from a three-level spatial perspective. As a result, this before-after study contributes to the understanding of the trade-offs between trunk-branch and trunk-feeder networks, while providing planning process recommendations for future large-scale public transport network overhauls.

1. Introduction

Large-scale public transport network (PTN) overhaul often affect large geographic areas and significant population. Such major service changes of PTNs can involve additions or replacements of transport modes (e.g., upgrade to a higher right-of-way and higher capacity), often related to land use changes (Nielsen et al., 2005; Walker, 2011). Moreover, the significance of the overhaul can be determined based on the percentage of routes affected, and include a combination of changes in the fare structure, spatial structure (e.g., route alignment, station location), and temporal structure (e.g., changing headways, service hours). The recent worldwide trend in PTN overhaul is to suggest transformation of direct radial routes (trunk-branch network) to a transfer-based system (trunk-feeder network), including timetable re-design (Vuchic, 2005; Hidalgo and Grafiteaux, 2008; Sivakumaran et al., 2014; Salazar Ferro and Behrens, 2015; Mees, 2010). Following this ongoing paradigm shift, as PTN overhauls are often made using public funding, their planning requires a careful balance between efficiency and equity. As an example of efficiency concerns, PTN planning has often been framed by the agency’s perspective, focusing on such aspects as cost (e.g., fleet size or operating cost) or resource utilization (e.g., vehicle crowding, service coverage, and deadheading) (Thompson and Matoff, 2003; Vuchic, 2005). Following the general argument of distributive justice theory, in addition to aggregate effects, planning decisions should consider the distribution of effects (Martens, 2012; Pereira et al., 2017; Linovski et al. 2018; Karner and Niemeier 2013). When thinking about equity, the assumptions that planners use is that passengers prefer fast, frequent, and direct PTN services without transfers (Wardman 2004; Garcia-Martinez et al., 2018; Vuchic 2005). However, as agency’s cost constraints require that some origins and destinations are connected using transfers as opposed to using direct routes, there are trade-offs between travel time...
and transfers in defining PTN alternatives. Within this context, planners are often facing a dilemma when trying to balance efficiency and equity, having at hand a difficult choice between multiple alternatives that are often equally (un)desirable (Rittel and Webber 1973). Thus, there is a need to inform further both theory and practice of PTN overhauls based on trunk-feeder principles.

While the principles for planning and general trade-offs between trunk-branch and trunk-feeder networks are well known from a theoretical standpoint (Gschwender et al. 2016; Jara-Díaz et al. 2012), there are very few real-world cases where the changes are documented from a user perspective. For example, minimum headways for individual PTN routes are often dictated by policy rather than demand. Thus, trunk-branch arrangement in some cases requires providing excess service on the branches to ensure the policy headway on the trunk section (Furth and Wilson 1981). Consequently, common trunk section may, depending on the overall demand pattern, have an even higher excess of capacity, leading to low vehicle load factors and therefore resource underutilization (Nielsen et al. 2005). Comparatively, a trunk-feeder network allows reducing this excess service on the trunk section and the number of separate vehicles and drivers, while still maintaining the policy-required headways on the feeder services. In addition, transition to trunk-feeder requires aiming for faster trunk section to mitigate some of the burdens caused by the added transfers between the trunk and feeder routes. Similarly, transfers can be made more convenient by implementing transfer synchronization or by increasing the service frequency (Vuchic 2005). What is theoretically expected is that areas close to the trunk route stations will typically have the same or better service than with direct bus routes, while negative aspects of a trunk-feeder system will concentrate on the PT users relying on feeder connections.

Given the premise that transitioning to a trunk-feeder network might result in an unequal distribution of benefits and burdens for end users, there is a need for further developing the knowledgebase for future PTN overhauls. Previously, there has been a stream of development in large-scale PTN planning and assessment methods. On the one side, a set of methods has mainly focused on using heuristic optimization approaches capable of mathematical formulation for complex large-scale PTNs (Guhaire and Hao 2008; Ibarra-Rojas et al. 2015; Bagloee and Ceder 2011; Cipriani et al. 2012). However, these methods are capable of only tackling parts of the network design problem and often do not consider the distribution of benefits in the assessment. Moreover, although providing an extensive body of knowledge in PTN planning, the application of these methods to actual large-scale PTN overhauls has remained limited. On the contrary, there has been a significant stream of development in PT service-equity assessment methods (Karner and Golub, 2015; Karner, 2018, b). While this stream of literature has focused on accessibility, often including aspects of land use, there has been a lack of case studies that would aim to understand direct effects of the PTN restructuring (Silva et al. 2017; Martens 2016). Moreover, previous development of PTN routing algorithms has focused dominantly on travel time. Thus, tradeoffs between travel time and transfers that are at the center of planners’ dilemma in planning trunk-feeder systems are not explicitly accounted for. These gaps have also been enhanced due to difficulties in accessing data or the extra effort required in modeling these large-scale changes (Karlaftis and Tsamboulas 2012; Karner, 2018; a; Karner et al. 2016).

Having in mind the need for drawing lessons from actual PTN overhauls, the recently completed first stage metro extension and subsequent PTN overhaul in the Helsinki Capital Region, Finland, provides an excellent opportunity for a case study. PTN overhaul in the Helsinki Capital Region has involved the transition from bus-based trunk-branch operation to trunk-feeder operation based on metro and bus combination. Similar to the dominant transport planning practice, cost-benefit analysis was utilized for assessment of this metro extension in the planning stage. Here, the gains and losses were assessed from an aggregate, i.e., utilitarian, perspective, where the focus is dominantly on the net benefits (Van Wee and Roesser 2013; Martens 2011; Beukers et al. 2012). Consequently, the wider distribution of effects for users was not a component of this PTN overhaul assessment. Recognizing the planning dilemma of simultaneously accounting for aggregate and distributive effects, the aim of this research is to assess the distribution of impacts for users after an actual large-scale PTN transformation to a trunk-feeder network. Following this analysis, the second aim is to provide lessons for planning future large-scale PTN transformations. Having in mind the need to balance efficiency and equity aspects, the analysis considers both the user as well as the macroscopic perspective, including the whole urban PTN. Drawing from gaps in the previous research in assessing changes from large-scale PTN overhaul, and accounting for the details of this particular case, this before-after study focuses on the following research questions:

1. What are the aggregate changes in travel times and numbers of transfers at different times of day?
2. What are the disaggregate changes in travel times and numbers of transfers, accounting for specific trip origin and destination locations, in relation to the metro expansion plan?
3. What is the relation between aggregate and disaggregate effects of the PTN overhaul?

With these aims in mind, this paper consists of the following six sections. The second section provides a background overview of studies about large-scale PTN overhaul analysis and PTN assessment methods for distributive effects. Section three describes PTN overhaul planning and implementation process in relation to the Helsinki metro extension, providing information about general changes in public transport service provision after the overhaul. Section four presents the open-data methodological framework for PTN overhaul assessment, including assessment measures, data, as well as the algorithm and analytical formulations using travel time and number of transfers. Section five shows the result of the multidimensional assessment of the West Metro effects, including aggregate and disaggregate effects at selected locations. The following section six provides a discussion of results, with implications for large-scale PTN assessment methodologies and planning processes, including explicit normative aspects. Finally, section seven concludes the paper with recommendations for further research related to methodological development and case studies of large-scale PTN overhauls.

2. Background

2.1. Previous studies on large-scale PTN overhauls

Previously, there has been a limited set of studies that measure effects on end-users caused by PTN overhauls. One of the first studies focused on several envisioned bus network overhauls and distribution of effects on different population groups in Belfast, using a supply measure combining PT frequency and coverage Wu and Hine (2003). A follow up study was performed after the realized overhaul by Blair et al. (2013). Here, spatial analysis of the changes in PT frequency was used to find areas winning or losing from the overhaul, revealing the stated effects of the overhaul on citizens’ daily life. El-Geneidy and Levinson (2007) measured the changes in number of jobs reached with car and PT between 1990 and 2000 in Minneapolis. This study focused on long-term changes in the PTN in a period with no large-scale redesigns. Despite some implemented changes in the PTN, the measured impact of these remained small. Another study on long-term (1996–2006) changes was performed on Toronto’s PTN (Foth et al., 2013). Contrary to the Minneapolis study, the Toronto PTN had several PT investments completed during the period, including a new metro branch with five new stations and seven new commuter train stations. The study linked the changes in access to jobs using PT to the spatial distribution of wealth on a neighborhood level. Farber and Fu (2017) used an
advanced continuous travel time measure with two example cases, Salt Lake City and Portland. The Salt Lake City case involved an expansion of the light rail and commuter train systems, while the bus services were cut back. In the Portland case the effects of a 10% service reduction were measured. Here, the comparison was made over a shorter period, between years 2011–2014 and 2009–2013 respectively. A further study on Salt Lake City focused on the distributive effects of changing fare system from flat fare to a distance based fare (Farber et al. 2014). Anderson et al. (2013) studied Minneapolis focusing on the timespan 2010–2030. Multiple combinations of land use and transportation networks were studied, featuring multiple PTN alternatives. Another study focused on the extension of the Rio De Janeiro BRT-system (Pereira 2019). A related body of PTN change literature studies the effects of high speed rail. Here, contrary to many studies focusing on city regions, these studies tend to be and focus on specific, defined changes in the PTN. The measures range from measuring travel time changes to one destination (Martínez Sánchez-Mateos and Givoni 2012), to the gravity-based weighted opportunities measure measuring jobs in distinct industries (Chandra and Vadali 2014). Furthermore, Cao et al. (2013) used a combination of several measures, such as weighted average travel time and cumulative opportunities index in studying the impacts of the Chinese high speed rail project. To conclude, previous large scale PTN overhaul studies have focused on the combination of land use and PT change. As a consequence, providing deeper implications for planning based on changes in PTN structure has proven especially difficult for the particular case of urban trunk-feeder system.

2.2. PTN distributive impact assessment methods

In the recent decades, there has been an increasing emphasis on developing assessment measures and methods from a user-centric perspective (Barabino and Di Francesco 2016; Curtis and Scheurer 2017). These previous measures have ranged from travel time, waiting time, in-vehicle travel time, to number of transfers and passenger cost. The development of distributive impact assessment methods has largely been under the paradigm shift towards accessibility planning (Curtis and Scheurer 2010). Thus, earlier studies have a strong anchoring in both the land use dimension of accessibility research and the demographic dimension of social justice research. In particular, the limitations in reaching destinations using PTN caused by location of residence or belonging to a disadvantaged group of population (i.e., accessibility gaps) have been a focus of several studies. One accessibility gap methodology focuses on comparing spatial match of the supply to the need for public transport in Melbourne (Currie 2010). A similar supply measure was used to study the accessibility gaps of elderly, low-income and, no-car population groups in Perth (Ricciodi et al. 2015). A more sophisticated approach used a cumulative opportunities measure, quantifying the number of services reachable within a fixed travel time budget. Kaplan et al. (2014) utilized this method combined with an advanced routing tool when studying spatial, vertical, and inter-generational equity in Copenhagen. A similar approach was used when studying vulnerable social groups in Montreal (El-Geneidy et al. 2016). Potential accessibility can also be measured without fixed travel time thresholds using the weighted travel time measure, where travel times are weighted with the available opportunities (Fayyaz et al. 2017).

A further variation of the potential accessibility measure is to apply a distance decay function to weight the destinations, in order to better reflect the actual travel patterns (Fransen et al. 2015). Karner (2018, b) used a set of gravity based accessibility measures to study the equity of the PTN in Phoenix. The accessibility measures were further used to evaluate individual routes in the PTN. Modeling actual behavior even more closely is possible through statistical models linking personal traits to travel behavior. Using this approach, it is possible to measure the accessibility for groups of people sharing the same profile (Järvi et al. 2018). This approach was used by Páez et al. (2012) when studying the accessibility of day care facilities while assuming various combinations of means of transportation and life situations. While most studies focus on spatial gaps, also the temporal dimension has been studied. For example, Farber et al. (2016) studies the temporal mismatch of PT demand and supply for population groups needing PT services in off-peak hours. In particular, the temporal dimension has been studied when analyzing the accessibility to food stores (Widener et al. 2015; Tenkanen et al. 2016). Apart from the distributive dimension, methodological differences also arise from the range of ways to define and calculate the travel component. On the one hand, these measures range from the PT supply and coverage typically measured through frequency and walking distance boundaries at the simplest. On the other hand, these measures include continuous travel time measures taking into account the PT schedule structure and the diurnal variations of travel time. In addition, advanced PT accessibility measures can take into account other travel impedance factors such as monetary cost (El-Geneidy et al. 2016), number of transfers (Kujala et al. 2018b), or a variety of travel time components (Kaplan et al. 2014). Furthermore, also the measurement scale impacts the results, as most studies use census zones as a basis of analysis. Although involving development of sophisticated models, accessibility gap studies have rarely been used to study PTN overhaul, or to provide lessons for trunk-feeder system planning.

3. Case study definition

3.1. PTN overhaul in Helsinki Metropolitan area

Helsinki Metropolitan area is often considered as an area with highly-developed PTN, and with high ranking in user satisfaction (HSL, 2018). Recently, there have been large investments in public transport network of the Helsinki Metropolitan area. One of these projects, the first stage of the West Metro project, finished in 2017, expanded the current east-bound metro line to the southwestern parts of the Helsinki Metropolitan area. At the cost of 1186 million Euros, metro network has been extended by 14 km, including eight new stations, five out of which include Park and Ride. The second stage of West Metro is currently under construction, and projected to finish in 2024. While the project was named after the central rail infrastructure, the project also involved substantial changes in the bus network, i.e., transforming a trunk-branch network to a trunk-feeder network. This was the case also with the initial east-bound metro section, opened in 1982, as the feeder-trunk system was retrofitted in the existing suburban fabric. The West Metro has seen a very long planning process with alignment, technical solutions and arguments for the project changing trough the decades even before the inauguration of the initial east-bound metro section.

Before construction, the West Metro was evaluated at several occasions, following for the most part standard practices in cost-benefit analysis. These analyses were based on travel forecasts and estimated construction costs, as well as comparison of the existing or improved trunk-branch bus network to the suggested metro option based on a trunk-feeder network. During this planning process, one of the main arguments for the metro option was a potential for increasing the land use density within the metro corridor (Espoon kaupunki, 2005; Länsimetro Oy, 2008; YTV 1987). Another argument for the metro option was a threat of increasing congestion of the road network for the reliability and speed of surface modes, such as buses. Travel time estimates were included in the forecasting model, and detailed examples of travel times between specific origin-destination pairs were provided as supplementary information. However, the travel time estimates were calculated using a static network representation and therefore only provided coarse estimates of the travel times.

3.2. Overview of changes in the service provision

Changes in the service provision included both the route planning as well as schedule recalculation. As a summary, Table 1 shows the
number of PT access points, route kilometers and vehicle kilometers for each mode before and after the opening of the West Metro. The statistics are based on single direction and describe the network for one weekday, thus providing an example for the PTN overhaul scale. In detail, each stop or platform included and referenced in the data set are calculated as separate, regardless of being a part of a station or terminal complex. Overall, vehicle kilometers for metro increased 66% while the service provided by bus is decreased by 9%. Contrasting, values for tram, commuter train and ferry are mostly unchanged. In addition to this table, the scale of the changes can be seen from Fig. 1 below. Panel on the left depicts PTN spatial layout and daily load (in vehicles per day) in the Helsinki Metropolitan area before the overhaul, while panel on the right of this figure depicts PTN the situation after the overhaul. Observing the changes in space, one can conclude that many direct bus lines going to the city center have been completely removed and replaced with feeder bus routes, converging mainly at two of the eight new metro stations.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Number of stops Before</th>
<th>After</th>
<th>Route kilometers Before</th>
<th>After</th>
<th>Vehicle kilometers Before</th>
<th>After</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tram</td>
<td>268</td>
<td>269</td>
<td>131</td>
<td>134</td>
<td>22,558</td>
<td>22,837</td>
</tr>
<tr>
<td>Subway</td>
<td>17</td>
<td>25</td>
<td>65</td>
<td>107</td>
<td>17,438</td>
<td>28,874</td>
</tr>
<tr>
<td>Rail</td>
<td>38</td>
<td>38</td>
<td>345</td>
<td>345</td>
<td>28,651</td>
<td>28,685</td>
</tr>
<tr>
<td>Bus</td>
<td>5662</td>
<td>5630</td>
<td>4954</td>
<td>4886</td>
<td>417,932</td>
<td>376,506</td>
</tr>
<tr>
<td>Ferry</td>
<td>4</td>
<td>4</td>
<td>12</td>
<td>12</td>
<td>242</td>
<td>242</td>
</tr>
<tr>
<td>Total</td>
<td>5989</td>
<td>5966</td>
<td>5507</td>
<td>5484</td>
<td>486,821</td>
<td>457,144</td>
</tr>
</tbody>
</table>

4. Methodology

4.1. Methodological framework

In order to draw implications for planners’ dilemma, special

![Table 1](image)

Fig. 1. The PTN of the study area before (panel A) and after (panel B) the opening of the West Metro and the feeder bus system weighted by frequency. The approximate capacity measured in the number of seats of the routes for the respective cases are show in panel C and panel D. Background map (c) OpenStreetMap contributors, (c) Carto.

attention has been dedicated to usefulness for planning practice, through interaction with practicing PTN planners during methodological development. To assess the distribution of benefits and burdens from a user-centric perspective, it is necessary to use a methodology capable at producing disaggregate results on a macroscopic level. While various types of cumulative opportunity indexes are excellent measures when characterizing an area, they do not perform well when assessing the potential benefits and burdens experienced by individuals in a trunk-feeder system. In particular, an increase in travel time or transfers between a single pair of origin and destination points may have severe consequences for some individuals. On the contrary, the same individual might not gain from improved accessibility to other locations. To overcome the challenges of producing an overview of the changes, the methodological framework is built with three main components, on three scalar levels (Fig. 2). In particular, the macro scale information is aggregated, the meso-scale is zone-based, and micro scale is focused on potentially least aggregated groups. By such combination of different levels of aggregation it is possible to enrich the aggregate levels from a user-centric perspective, this would require further sources of data and more sophisticated application procedures that planning agencies often avoid (Silva et al. 2017; Boisjoly and El-Geneidy 2017). Moreover, special attention has been dedicated to the use of open data as an input for analysis procedure, as this has been recognized as one of the major opportunities for PTN planning (Davidsson et al. 2016; Kujala et al. 2018a). Following the principles of open science, the scripts used for producing the results are released online (https://github.com/jweckstr/westmetro_scripts). Details of each assessment scale in the framework are explained in the following subsections.

4.2. Data

Similarly to many recent studies (Fransen et al. 2015; Farber et al. 2016; Fayyaz et al. 2017; Karner, 2018,b; Hadas 2013), our before-after analysis uses two public transport schedule datasets in the General Transit Feed Specification (GTFS) format (for a description of the format, see https://developers.google.com/transit/gtfs/). These data sources are openly provided by the Helsinki Region Transport (HSL) (see https://www.hsl.fi/en/opendata). The first dataset represents the schedule before the West Metro and the second the new schedule with the West Metro and feeder routes in operation. The dates of the schedules used in this case study are for the Wednesday, 25.10.2017, and Wednesday, 10.01.2018, respectively, as representative analysis dates without major schedule changes. In addition, this schedule data is complemented with street-network-based walking distances, calculated between stops that are 2 km or less apart using OpenStreetMap (OSM) data. As this before-after analysis relies on comparisons of stop-to-stop travel measures between same locations, it was necessary to make sure that each dataset included the same stops. To this end, before and after databases were supplemented with the stop locations missing.

4.3. Computing origin-destination travel times and transfers

The travel travel times and transfer values were calculated using a modified version of the Connection Scan Algorithm (CSA), implemented in the Python programming language, included in the gtfspy package (https://github.com/CxAalto/gtfspy) (Dibbelt et al. 2017; Kujala et al. 2018b). In this algorithm, every connection between adjoining stops in the transit schedule and connecting walking connections generated based on the schedule are scanned through in reversed temporal order. The walking connections in this methodology have a

Fig. 2. Framework showing the principles of aggregation and the outputs for different scales of analysis.
maximum distance of 2 km and the walking speed is set to 70 m/min. The algorithm collects a set of journey alternatives that are Pareto-optimal with regards to departure time, arrival time and number of transfers. The Pareto-optimality of trips is based on the trade-off between travel time and transfers: a trip is accepted as Pareto-optimal if an improved solution for a criteria cannot be found without declining any other criteria. In addition, the number of transfers is not limited in the routing process. However, a minimum transfer time of 3 min is applied, which prohibits journeys with transfers that are likely to fail in real situations. As a side-effect, this also discourages transfers in the routing, which is a general users’ tendency. A travel time profile is created using the calculated Pareto-optimal trips, continuously describing the total travel time (including waiting time before the trip) between the origin and the destination, while also considering the number of transfers needed to reach the destination. The travel time profile in this methodology is calculated for a one-hour departure-time interval. However, the actual routing is calculated for three consecutive hours allowing also longer journeys to complete. Based on the travel interval. However, the actual routing is calculated for three consecutive

pro number of transfers needed to reach the destination. The travel time between the origin and the destination, while also considering the routing, which is a general users’ tendency. A travel time profile is created using the calculated Pareto-optimal trips, continuously describing the total travel time (including waiting time before the trip) between the origin and the destination, while also considering the number of transfers needed to reach the destination. The travel time profile in this methodology is calculated for a one-hour departure-time interval. However, the actual routing is calculated for three consecutive hours allowing also longer journeys to complete. Based on the travel time profile generated, it is possible to produce performance measures as described by Kujala et al. (2018b). The travel time profile was then used to calculate a mean travel time between all stops in the study area and the mean number of transfers for the fastest path trips. In particular, the mean travel time approach assumes an informed PT user that always chooses the fastest trip option, but leaves at a random time. In addition, calculating the number of transfers while in the same time considering the travel time creates more reasonable results than using methods based on a static network (Kujala et al. 2018b).

4.4. Assessment measures

Following the above-mentioned premises and research questions, assessment measures include three parts with different levels of aggregation. The basic unit of analysis for travel time is the average origin-destination travel time ($TT_{i,j}$), describing the average time to reach the destination $j$ from the origin $i$ when travel takes place spontaneously without planning, that is taking into account the pre-journey waiting time. $TT_{i,j}$ can be calculated as:

$$TT_{i,j} = \frac{1}{t_{end} - t_{start}} \int_{t_{start}}^{t_{end}} \tau_{j}(t) dt$$  

(1)

where $t_{end}$ and $t_{start}$ are the end and start time of the analysis period, and $\tau_{j}(t)$ the travel time from access point $i$ to access point $j$ as a function of time.

For transfers we calculate the number of vehicle transfers on fastest paths, $NT_{i,j}$, which calculates the mean number of required transfers when using the fastest route. Please note, that the word transfer here also includes the first access to a PT route, not only transfers between other stops

$t in any of the other categories (\tau start)$.

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$t in any of the other categories (\tau start)$.

$TT_{i,j}$ can be calculated as:

$$NT_{i,j} = \frac{1}{b^{f/O}} \int_{t_{start}}^{t_{end}} b^{f/O}(\tau) dt$$  

(2)

where $b^{f/O}$ is the number of transfers on the next fastest-path journey departing at time $\tau$ or later. Based on these, the mean travel time to all destinations (MTT$_i$) and mean number of transfers to all destinations (MNT$_i$) are calculated, corresponding to the average travel time and transfer, respectively, needed to reach all other stops. These measures are calculated as:

$$MTT_{i} = \frac{1}{n} \sum_{j=0}^{n} TT_{i,j}$$  

(3)

$$MNT_{i} = \frac{1}{n} \sum_{j=0}^{n} NT_{i,j}$$  

(4)

where $n$ is the number of stops with a valid path to the stop in question.

These mean measures provide an overview of changes, but are not capable of showing the effects on a stop-to-stop basis. The last set of performance measures are the most aggregated, representing the system level averages, giving an indication of the overall direction of changes. These measures are called *all to all mean travel time* (ATT) and *all to all mean number of transfer* (ANT) and are calculated as:

$$ATT = \frac{1}{n} \sum_{i=0}^{n} MTT_{i}$$  

(5)

$$ANT = \frac{1}{n} \sum_{i=0}^{n} MNT_{i}$$  

(6)

where $n$ is the total number of valid stop entries.

4.5. Analysis zones and focus locations

To study how the travel time changes in different locations in relation to the metro extension, the study area has been divided into five assessment zones (AZ) based on the location in relation to the metro expansion (Fig. 2). In this zoning arrangement, each public transport stop is a member in one of the zones. In the case a station could belong to multiple zones, classification preference is assigned ordinarily, in the following order which accounts for the position of the stop with respect to the network overhaul. The first AZ consists of the areas close to the new metro stations (*new metro stations*). The second zone consists of areas that have lost the direct bus connections to the city center and will rely on feeder buses to the new metro stations (*feeder bus area*). Here we included stops from which at least half of the fastest path trips to the city center passes via the new metro extension after the metro has been introduced. This step was necessary due to a “soft” boundary between the area relying on feeder buses and the area to the north where there are the options on using the commuter trains, with or without feeder buses or direct bus connections to the city center. The third AZ consists of the areas around earlier metro stations (*old metro stations*), the fourth AZ of areas around commuter train stations (*commuter train stations*). The fifth AZ includes all other stops that do not fit in any of the other categories (other stops), and that were not considered directly in the PTN overhaul. The zones centered around metro or commuter train stations are defined by a 800 m walking distance threshold, in accordance to a commonly used estimation of a typical walking distance to transit discussed by Guerra et al. (2012). In addition to the AZ, a set of six stop locations were selected to represent the most detailed level of analysis and thus to demonstrate the spatial sensitivity of the overhaul impacts. Three stops are located along the metro in the city center, a key transfer point and destination for PT in Helsinki. The additional three reference stops are located in the area of the PTN overhaul.

5. Results

5.1. Aggregate changes

The ATT and ANT for different times of day before and after the West Metro are shown in Table 2. The average travel time to reach all destinations is roughly one hour for all time periods within the study

Table 2

<table>
<thead>
<tr>
<th>Time</th>
<th>ATT</th>
<th>ANT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before</td>
<td>After</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7-8</td>
<td>0:58:27</td>
<td>0:59:06</td>
</tr>
<tr>
<td>12-13</td>
<td>1:00:56</td>
<td>1:01:17</td>
</tr>
<tr>
<td>16-17</td>
<td>0:58:10</td>
<td>0:58:38</td>
</tr>
<tr>
<td>21-22</td>
<td>1:01:41</td>
<td>1:02:31</td>
</tr>
</tbody>
</table>
Furthermore, 2.4–2.5 transfers are required when using the fastest route option. The indicators suggest a small increase of ATT at all times of day, especially in the late evening. However, there is a slight decrease in ANT, suggesting a reduction in the average number of transfers required. In addition to these most aggregate measures, the spatial distribution of MTT and MTB change reflects the area where the PTN overhaul took place. For this figure, MTT and MNT measures are calculated considering all the PT access points as potential and equally-valued destinations, for departures between 7:00 and 8:00 AM, i.e., morning peak hour. Presented in the right panel of Fig. 3, the aggregated changes for MNT follow a similar pattern as MTT. When considering all destinations, the new metro stations areas have an average MNT decrease of up to 0.6, while the average MNT for the feeder bus areas will increase up to 0.5. (See Fig. 4).

5.2. Changes by analysis zone

The distribution of TT changes gives more insight on the effects for specific origin-destination combinations (Panel A in Fig. 5). The distribution of change shows both increased and decreased travel times for most categories. However, TT for new metro stations is predominantly improving, with up to 15 min shorter travel times and only a few destinations with increased TT. In comparison, the main exception are travel times between stops in the new metro stations AZ and feeder bus area AZ, which has a even distribution between positive and negative changes in TT. Moreover, TT for the feeder bus area AZ is mostly increasing, even beyond 15 min, with very few destinations with improved values. However, there is still a number of origin-destination pairs where the changes are small. For transfers (Panel B), the direction of change are similar when considering the corresponding origin and

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Fig. 5. The change in travel time (panel A) and number of transfers (panel B) between and within the AZ in the morning peak hour.
destination zones. The changes tend to be within an increase and decrease of one transfer, for trips directly affected by the overhaul. However, the new metro stations AZ experience decreases of up to one transfer on some trips to the old metro stations AZ. As can be expected, TT of trips completely outside the West Metro corridor are mostly unchanged, as can be seen in the cells describing TT changes within and between old metro stations, commuter trains stations and other stops AZs in Fig. 5.

5.3. Impacts for selected locations

In order to highlight changes at representative locations, Fig. 6 shows the changes in TT and NT. In the upper part of the figure, one can observe the sensitivity of changes for city center locations, i.e., Kamppi, Lasipalatsi and Rautatieti. In particular, TT and NT increases for Kamppi and Lasipalatsi stops overall, with the only exception being stops in the Otaniemi area. However, only a few hundred meters east is the tipping point, where the increase in NT caused by the introduction of the feeder bus system is neutralized by the previously required additional transfer. Thus, to Rautatieti stop and locations further east along the metro, NT is not increasing for the feeder bus area, while NT is decreasing for stops in the new metro station AZ. Travel time changes follow a similar pattern, although less abrupt. In particular, Kamppi area has the highest increases in TT, with increases of over 20 min possible. At Rautatieti stop, the increases are limited to 10 min, with a larger area having a reduced travel time.

Soukka, Matinkylä and Otaniemi are locations within the West Metro corridor, that is the metro station vicinities and the feeder bus

<table>
<thead>
<tr>
<th>To</th>
<th>A (Kamppi)</th>
<th>B (Lasipalatsi)</th>
<th>C (Rautatieti)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔNT_{i,j}</td>
<td>[Image]</td>
<td>[Image]</td>
<td>[Image]</td>
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<tr>
<td>ΔTT_{i,j}</td>
<td>[Image]</td>
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<table>
<thead>
<tr>
<th>To</th>
<th>D (Soukka)</th>
<th>E (Matinkylä)</th>
<th>F (Otaniemi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔNT_{i,j}</td>
<td>[Image]</td>
<td>[Image]</td>
<td>[Image]</td>
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<td>ΔTT_{i,j}</td>
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Fig. 6. TT_{i,j} and NT_{i,j} to specific stop locations, during the morning peak hour. Background map (c) OpenStreetMap contributors, (c) Carto.
area. Soukka and Matinkylä experience similar patterns for NT and TT change. However, the TT change is much higher in Soukka, the station being deep in the feeder bus area AZ, compared to the Matinkylä stop which is on the border between the feeder bus area AZ and the new metro station AZ. On the contrary, the effects for Otaniemi are completely different. There are almost no areas with increases in NT nor TT. The decreases in NT and TT correspond the metro stations, both old and new. Furthermore, the areas relying on transfer points west of Rautatientori also show improvement.

6. Discussion

6.1. Distribution of PTN overhaul effects

The study attempts to give an accurate and nuanced description of the potential effects for individual PT users. Using travel time and transfer-based measures makes the direct effects of the PTN overhaul easier to grasp. Findings indicate that travel time and transfer benefits are concentrated around the metro stations both new and old, while the areas relying on feeder buses are generally carrying the burdens of increased travel time. This effect was reflected in both the aggregate measures, mean travel time to all destinations (MTT) and mean number of transfers to all destinations (MNT) and the disaggregate measures average origin-destination travel time (TT) and number of vehicle transfers on fastest paths (NT). However, this specific case of the West Metro is strongly influenced by the fact that the metro did not increase the speed of the trunk section but merely aligned the trunk section differently. Furthermore, the results show that the areas benefiting from the metro were fairly well connected also before the metro, while some of the most severe travel time increases are imposed on areas with the longest initial travel times. This is further accentuated with the fact the PT users in these areas are also often required to transfer more. Thus, based on the results, the changes in travel time and number of transfers from the West Metro project were unequally distributed from a spatial perspective.

The general trend was larger travel time savings in the vicinities of metro stations close to the city center and locations further away from the former bus trunk section. Consequently, station locations between the city center and the northward bend of the new metro section gained travel time savings of up to 10–15 min in MTT, while stations furthest to the west gained only 5 min MTT. The connections between metro station vicinities are improved where the past system lacked direct connections.

While the areas relying on feeder buses in general experienced increased travel times, in some areas travel times remained unchanged or even decreased. The differences between the past and new route alignments is the main reason of these differing effects. The most important factors are the relative closeness of the metro stations compared to the motorway and the degree in the high speed and direct alignment of the highway was utilized by the direct bus route. In particular, areas where a large proportion of the distance of the bus system in the past was covered on streets see small positive and negative effects, while areas where the high speed and direct alignment of the highway was utilized see strong MTT increases up to 15 min. The former is the case in areas north of the metro alignment while the latter occurs in the west and along the motorway. Furthermore, in some instances also the old bus system relied on transfers for connections towards the city center. In these cases the change to the metro improved travel times.

The areas outside the new metro corridor show only minor changes in mean travel time, with a small overall increase. This may be interpreted as a “shadow” effect of the changes seen in the West Metro corridor, where the stops with increased travel time dominate. When considering particular origins and destinations where changes occur, the positive effects are concentrated along the old metro section and areas that are well connected to the metro in the eastern parts of the city. The clear loosener is the former terminus of the motorway bus system (Kamppi), as well as the areas extending northward from this location (see Fig. 6). These results suggest that the metro is not fast enough to overcome the lost time in the feeder system, longer alignment of trunk section, and the increased number of stops. Furthermore, the results suggest that the changes brought about by the second phase of the West Metro are most likely not improving the MTA of the future metro stations beyond the trunk-branch system. The situation for peripheral areas relying solely on feeder buses will likely stay as is.

6.2. Implications for planning methods and processes

Contrasting the findings from this study with theoretical arguments about effects of trunk-branch and trunk-feeder networks highlights several aspects that should be taken into account in the future PTN overhaul planning. At the center of this reflection, we have to recognize an irreducible planner’s dilemma in finding the right balance between aggregate and disaggregate effects. Contrary to the dominant utilitarian logic often used in spatial planning, which focuses on aggregate effects, this study highlights the importance of distributional effects from PTN transformation to a trunk-feeder network. In this particular context, we have to recognize that Helsinki Region Transport System Plan includes an explicit focus on accessibility in the region (HSL, 2015). This is an excellent example of the transition in planning practice, changing the focus from average vehicular speeds to the capability of reaching a destination. In this case study context, information about accessibility is even more important having in mind an equal access to opportunities for everyone, which is a dominant value of the Finnish society (Rantanen et al. 2015). However, the idea of absolute equality is often challenged by the basic properties of transport systems and the underlying center-periphery topography. Essentially, the explanation is rather straightforward – it is often difficult to have equal travel time for all the citizens across the region to, for instance, Helsinki city center. Thus, the core of planner’s dilemma is how to find the acceptable balance of the unequal effects from PTN overhaul, while coping with the multitude of design dimensions of trunk route alignment and stop locations. In addition, it would be important to highlight the notion that planner does not face a binary decision between trunk-branch and trunk-feeder network. On the contrary, just as in the case of West Metro, where some direct bus routes have been introduced for areas with largest travel time increase, network design decisions are on a continuum. In such a network design process, while cumulative cost-benefit analysis may be a useful step for assessment, it is not sufficient when considering the consequences for individuals or for accounting for non-monetary effects. Besides accounting for cost-benefit ratio, the use of variable criteria weights within a multi-criteria framework would open up more opportunities for deliberation about the effects for different citizen groups. Furthermore, as an example of aspects difficult to measure monetarily, we have to recognize that many transport experts would agree that investment in West Metro is justified as a strategic mechanism for shifting land use policy towards a more sustainable direction.

Emphasizing on the process of planning, dilemma situations require a planner to make a difficult choice between two or more alternatives, that are often equally (un)desirable. In this process of planning, a planner might need to accept a dialectic between two contrasting views on social justice – namely utilitarian and Rawlsian logic. Similarly, we have based our methodological approach following both. The central message of classical utilitarianism is that an act is morally right if it maximizes the difference between the total amount of benefits and total amount of burdens for all people. Following this idea, we have to be thoughtful about the aggregate effects and aggregate resources of our transport systems. For example, we would certainly want that our PT system results in the lowest possible amount of total CO2 tons emitted. Following the utilitarian approach in this case study means a focus on calculating average net change in travel time and number of transfers. However, what the findings above tell us is that a utilitarian approach is
useful as an overview of the impacts, but inevitably does not reveal much about the distribution of impacts. Thus, solely focusing on aggregate benefits would misinterpret the implications for users, as benefits and burdens brought about by a PTN overhaul may vary between users even in the same spatial location. Contrary to the classical utilitarianism, distributive theories of justice underline the fact that the distribution of effects matters, as it is not always desirable to violate significantly the right of the few for the sake of the many. In one of the most influential theories of distributive justice, John Rawls recognized that inequalities may exist, as long as the benefits from the inequalities are accessible to all, and these inequalities are distributed to benefit the least well-off (Rawls 1971). Following this line of logic, if one analyzes PTN impacts spatially, adverse inequalities will inevitably be noticed, but it matters how adverse they are for particular people affected. From the findings above, one can conclude that distribution of changes on a zonal level, both within and between zones, provides a more nuanced view on the impacts that different origin-destination pair categories experience. This contrast between aggregate and distributed effects is at the core of this difficult choice that PTN planner would have to face. However, just as many other dilemmas that often do not have a straightforward resolution, recognizing that they exist is a major step in advancing further reflection.

Focusing at the assessment methods, there are other detailed aspects to take into account in the future PTN overhaul planning processes. As in this case study, effects for specific locations can help in understanding aspects that have been neglected in the original impact assessments. Here, one has to recognize that the point of measurement will heavily frame the results. For example, measuring effects at the former bus terminus of the trunk-branch network will favor the bus, indicating an increase in number of transfers for all areas relying on feeder buses. On the contrary, measuring effects at locations further away along the metro route will favor the metro, indicating a decrease in number of transfers in all areas within walking distance to the metro stations. Certainly, neither of the measurement locations are wrong as they represent the travel patterns of many people, and will be affected by network structure properties. Moreover, effects will differ due to the asymmetry of effects due to the changes in schedule structure. The trunk-branch system has a more asymmetric service structure with frequent service in the peak direction and in some cases different route variants running in the opposite direction. Conversely, the trunk-feeder system is providing a more even service in both directions. The pattern of travel time changes are thus not only sensitive to location but also to the direction of travel. However, the central point is that travel time changes cannot be reliably assessed trough a narrow selection of origin-destination pairs as was made in the original impact assessments. Thus, in order to provide a broader understanding of the benefits and burdens from large-scale PTN overhaul, assessment practice in the future has to include a combination of stations, such as terminus stations of the trunk-branch network, and stations further away from the new trunk section.

The results of this research showed that the generated total travel times for the metro option in the planning phase were optimistic compared to the realized schedules. In fact, travel time estimates computed based on static network based transport models may not be accurate enough to take into account the complexities of a schedule-based PT system. In the worst case, the travel time estimates may be misleading and lead to inferior designs. Metaphorically speaking, just as our lives do not happen in static map-based plans, our PT trips do not happen only on map lines without schedules. Not accounting for the fact that PTNs are temporal networks have most likely influenced both the results from cost-benefit analysis and consequently the decision process itself. Basing the argument on travel time estimates that neglect nuances of time calculation mechanisms might also undermine the existing trust in Finnish planning institutions, especially in the cases of such large public investments. The challenges identified here directly relate to the components of the planning process itself. For instance, planning processes for PT investments are often dominantly focused on the infrastructure and network planning, where the scheduling process starts only after the investment decisions has already been made. In turn, further development of planning processes would require a more thorough planning and assessment of the PT network and schedule at an earlier stage. Nowadays, these analysis steps can certainly be made possible with the increased availability of suitable planning support systems and the increased computing capacity. However, such recommendations for planning processes ultimately lead to the question of roles and responsibilities of stakeholders within those processes and their broad goals. Ultimately, we arrive to the question of whether large-scale PT investments and system overhauls should be planned in a more human-centered order, taking the desired service level for users as a starting point rather than the map-based infrastructural outlines.

7. Conclusion

In order to provide implications for balancing efficiency and equity in planning practice, the study presented here developed a methodology for quantifying the effects of large scale PT overhauls from trunk-branch to trunk-feeder network. This methodology is applicable for any set of longitudinal PT schedule data. The methodology brings user-centric performance measures to a macroscopic scale, enabling a more nuanced assessment of PTN overhauls. The impacts of transformation from a trunk-branch network to a trunk-feeder network were analyzed using two main approaches. The first approach is following a utilitarian logic, assessing the average net change in travel time and number of transfers. The second approach assumes a distributive justice standpoint, where changes in travel time and transfers are assessed in a disaggregate and distributed manner. As seen from the findings, the transition from a direct bus network to a feeder-trunk network has different implications for PT users if observed from an aggregate or disaggregate standpoint. In particular, the number of transfers required for passengers relying on feeder buses might increase, while the service level closer to the stations might improve. Having a detailed look at the distribution of effects, the trunk-feeder system might both mitigate and aggravate the inherent inequality caused by location within a city.

7.1. Limitations and future research directions

This research focused on potential mobility from a user-centric perspective. However, to enhance interpretability and as a consequence of solely relying on open data sources, the model has omitted several important factors impacting the individual's ability to utilize PT. Thus, further research could take into account other user traits or capabilities, such as household structure, social status or age (Páez et al. 2012), perceived accessibility (Lättman et al. 2018), or walking capabilities. In particular, further integration of walking and PT routing is necessary for creating accurate results. However, for computational reasons walking distances needs to be cut short, increasing the possibility of erroneous results on trips where walking is competitive. On the contrary, methodological development can account for walking distances within large PT stations and terminals, as these are rarely included in openly available walking network datasets. For simplicity, in this research only the fastest paths are considered. Moreover, there is a need to include service reliability indicators or aspects of PT fare scheme (El-Geneidy et al. 2016), eventually leading to generalized cost approach that could produce more robust results. However, when considering the differing preferences of PT users in relation to differences in PT system, a more advanced approach would be to compare the results of several preference profiles.

In addition, this study contains some limitations regarding generalizability of findings. Due to the case approach, the results regarding the justice dimension of trunk-feeder networks are not generalizable. Furthermore, the case of the West metro is fairly unusual with the new trunk section not increasing travel speeds. Thus, for better
generalizability, it would be necessary to study several real-life cases of transitions from trunk-branch to trunk-feeder networks, and further assess PTN transitions. In addition to more active analysis of large-scale PTN overhauls worldwide, made easier by the widespread of open data sources, it is also necessary to continue investigating the possibilities for distributive justice assessment in the planning processes. There is clearly room for research on planning frameworks better adapted at integrating individual level impact assessment within the overall planning process, especially by enhancing public engagement as part of assessment procedures. With this in mind, one research strand should continue investigating the possibilities that public engagement has for development of usable and useful planning support systems (Stewart 2017; Mladenovic et al. 2018; te Brömmelstroet, 2017). As another research strand, there is a need for further integration of route and schedule planning methods, often based on operations research approaches, and assessment methods, often based on GIS approaches. Despite some epistemological differences between these scientific groups, a common user-centric approach provides an opportunity for further methodological refinement. This development of analytical models will certainly benefit from the ongoing theoretical conceptualizations in the domain of transport and mobility justice. However, an action-science approach, focused on understanding the dynamics and responsibilities in planning processes might be a necessary complementary effort, if such planning support systems are to be co-created and adopted by practitioners. In this context, continuing the emphasis on open science and open data mode of thought should be a necessary underpinning for long-term, collaborative, development.

Declaration of Competing Interest

None.

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References


