Computers, Environment and Urban Systems 67 (2017) 41–54

Contents lists available at ScienceDirect

Computers, Environment and Urban Systems

journal homepage: www.elsevier.com/locate/ceus

Travel times and transfers in public transport: Comprehensive accessibility analysis based on Pareto-optimal journeys

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ARTICLE INFO

Article history:
Received 3 March 2017
Received in revised form 28 August 2017
Accepted 28 August 2017
Available online xxxx

Keywords:
Transit
Routing
Temporal distance profile
Temporal network
GTFS
OpenStreetMap

ABSTRACT

Efficient public transport (PT) networks are vital for well-functioning and sustainable cities. Compared to other modes of transport, PT networks feature inherent systemic complexity due to their schedule-dependence and network organization. Because of this, efficient PT network planning and management calls for advanced modeling and analysis tools. These tools have to take into account how people use PT networks, including factors such as demand, accessibility, trip planning and navigability. From the PT user perspective, the common criteria for planning trips include waiting times to departure, journey durations, and the number of required transfers. However, waiting times and transfers have typically been neglected in PT accessibility studies and related decision-support tools. Here, we tackle this issue by introducing a decision-support framework for PT planners and managers, based on temporal networks methodology. This framework allows for computing pre-journey waiting times, journey durations, and number of required transfers for all Pareto-optimal journeys between any origin–destination pair, at all points in time. We visualize this information as a *temporal distance profile*, covering any given time interval. Based on such profiles, we define the best-case, mean, and worst-case measures for PT travel time and number of required PT vehicle boardings, and demonstrate their practical utility to PT planning through a series of accessibility case studies. By visualizing the computed measures on a map and studying their relationships by performing an all-to-all analysis between 7463 PT stops in the Helsinki metropolitan region, we show that each of the measures provides a different perspective on accessibility. To pave the way towards more comprehensive understanding of PT accessibility, we provide our methods and full analysis pipeline as free and open source software.

1. Introduction

Efficient, easy-to-use public transport (PT) networks are a vital element of functional, sustainable cities (Banister, 2008; Newman & Kenworthy, 1989). If planned carefully, PT is a space efficient transport mode with low emission levels, offering mobility for users spanning all ages and income levels (Church, Frost, & Sullivan, 2000). One prerequisite for good PT network planning is a set of tools and measures for evaluating PT network designs. In particular, tools for measuring PT travel impedance are required, as they help practitioners identify potential problems, such as poor connectivity, and assess the impacts of public transport investments and network redesigns.

Among urban transport modes, PT has three distinguishing features that make the assessment of travel impedance difficult. First, PT journeys are usually multi-modal, as a completed journey requires access and egress legs with another mode, typically walking. Second, unlike other modes, PT is a scheduled service that offers connections between stops only at specific points in time. Third, PT provides services through a network that should operate efficiently while maintaining significant spatial coverage. These PT features are also transferred to the passenger perspective. Common factors affecting PT user experience include waiting times to departure, access and egress walking distances, journey durations, and the number of required transfers.

The challenges in assessing PT travel impedance have resulted in a variety of analysis frameworks. While some studies have used static representations of PT networks for computing travel times (Curtis & Scheurer, 2010; Delmelle & Casas, 2012; Mavoa, Witten, McCreanor, & O'Sullivan, 2012; O'Sullivan, Morrison, & Shearer, 2000; Tribby & Zandbergen, 2012) and the number of required vehicle boardings (Hadas & Ranjitkar, 2012; Wang & Yang, 2011), the recent trend has been towards more accurate modeling of travel

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http://dx.doi.org/10.1016/j.compenvurbsys.2017.08.012
0198-9715/

times using actual PT schedules with information on departure and arrival times (Benenson, Ben-Elia, Rofé, & Geyzersky, 2017; Benenson, Martens, Rofé, & Kwartler, 2011; Farber & Fu, 2017; Farber, Morang, & Widener, 2014; Lei & Church, 2010; Salonen & Toivonen, 2013). To address the dynamic nature of PT travel time, travel times have been computed at different times of day with time resolutions as high as 1 min (Farber & Fu, 2017; Farber et al., 2014; Owen & Levinson, 2015). This methodology has enabled meaningful computation of the minimum and maximum travel times together with the estimation of typical service headways using Fourier analysis of the travel time profile (Farber & Fu, 2017). Moreover, the spatial resolution of travel time analyses has been increasing, and recently door-to-door travel times have been computed even at the level of individual buildings (Benenson et al., 2017).

Despite the ongoing progress, previous research leaves room for methodological improvements in assessing PT travel impedance. Especially, we have identified two areas of improvement related to quantifying pre-journey waiting times, journey durations, and transfers, which are known to cause discomfort to PT users (Iseki & Taylor, 2009; Litman, 2008; Wardman, 2004). First, how PT travel time is measured varies across studies and it is typically considered single-faceted. While some studies only aim to capture the journey duration (Benenson et al., 2017; Salonen & Toivonen, 2013; Tenkanen, Heikinheimo, Järv, Salonen, & Toivonen, 2016), others include the pre-journey waiting time as part of PT travel time (Farber & Fu, 2017; Farber et al., 2014; Lei & Church, 2010; Owen & Levinson, 2015). The former approach effectively assumes that the PT user plans her travel according to schedules, while the latter assumes that travel takes place spontaneously. Despite this, there has been little discussion on the differences of these two alternative definitions of PT travel time. The second area of improvement relates to quantifying the required number of transfers between an origin-destination pair. Even though transfers are an integral part of PT travel impedance, there are no studies quantifying the number of PT vehicle boardings between origin-destination pairs that would fully take the time-dependence of PT operations into account.

One potential reason why the above aspects of PT travel impedance have not been considered before might be rooted in the methodology used by most PT accessibility studies. In particular, many studies rely on Dijkstra's algorithm for computing travel times in the PT network (Dijkstra, 1959). However, Dijkstra's algorithm can only optimize PT travel time while it ignores the number of required transfers. Using Dijkstra's algorithm also necessitates that PT travel times are sampled, *i.e.*, travel times computed only at certain departure times. Even though sampling yields an approximate picture of the dynamic travel time profile, disentangling pre-journey waiting times from journey durations remains difficult.

These challenges can be overcome by realizing that PT travel times and numbers of required boardings are determined by the journey alternatives enabled by the PT network, assessed through the concept of *Pareto-optimality*. Pareto-optimality can be explained with a simple example. Let us assume that a PT user is traveling from an origin O to destination D at time t, and compares PT journey alternatives. Further, let us assume that her decision-making criteria only include the time to reach the destination (t_{arr}-t) and the number of PT vehicles (b) she needs to board. Then, each PT journey alternative can be summarized as a tuple (t_{arr}-t, b). If the user prefers to reach her destination fast and dislikes transfers, *i.e.* prefers small values of t_{arr}-t and b, her rational choice alternatives correspond to the Pareto-frontier of all journey alternatives, as illustrated in Fig. 1.

The above setting corresponds to spontaneous travel, where the departure time of the travel is pre-determined. However, in reality a user can plan and adjust her departure time based on PT schedules. Therefore, the departure times (t_{dep}) of the journey alternatives should be taken into account too. Then, PT journeys are summarized as triplets (t_{dep}, t_{arr}, b). To minimize the journey duration ($t_{\mathrm{arr}} - t_{\mathrm{dep}}$), it is now natural to prefer large values of t_{dep}. Given all journey alternatives, the Pareto-frontier contains the fastest journey alternatives for reaching the destination with different numbers of boardings, at all departure times. Such sets of Pareto-optimal journey alternatives fully describe the dynamic accessibility between origin–destination pairs in terms of journey durations, pre-journey waiting times, and transfers.

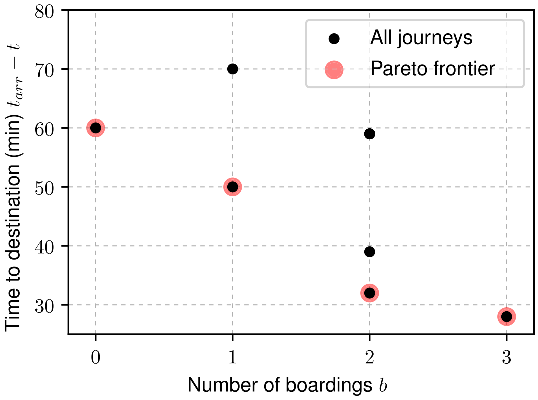

Fig. 1. An example set of Pareto-optimal journey alternatives for a certain departure time t. Note that for each Pareto-optimal journey alternative, there are no other journey alternatives that would be better both in terms of number of boardings b and the time to reach destination, *i.e.* temporal distance, $t_{\mathrm{arr}} - t$.

The routing algorithms used in typical PT accessibility studies cannot compute Pareto-optimal journey alternatives over a given time interval. However, many algorithms specifically tailored for PT have been developed recently (Bast et al., 2015; Delling, Pajor, & Werneck, 2012; Dibbelt, Pajor, Strasser, & Wagner, 2013). While the main motivation in their development has been to decrease the response times of on-line journey planners, they can also compute all Pareto-optimal journey alternatives between an origin–destination pair that depart within a given time interval.

However, to the best of the authors' knowledge, such Pareto-optimal journey alternatives have not been used as the basis of PT accessibility studies, and there is no methodological framework for their analysis. Thus, we develop such a framework based on temporal networks methodology (Gallotti & Barthelemy, 2015; Holme & Saramäki, 2012; Holme & Saramäki, 2013). Especially, we show how sets of Pareto-optimal journey alternatives can be used to construct *temporal distance profiles* that provide full temporal information on the time to reach a destination over a specified time interval (Pan & Saramäki, 2011). These profiles can be augmented with information on the required numbers of vehicle boardings. Using the temporal distance profiles, we define the best-case, mean, and worst-case measures for PT travel time and the number of required vehicle boardings. Additionally, we study the trade-offs between travel time and the required number of vehicle boardings.

Regarding our analysis pipeline, we adopt an open science approach in terms of data and software. For PT timetables, we use data provided in the General Transit Feed Specification (GTFS) format, and for computing the walking network between PT stops, we rely on open data provided by the OpenStreetMap project (OpenStreetMap contributors, 2017). Moreover, we provide our full analysis pipeline as free and open source software.

To demonstrate the utility of our methodology for PT planning, we discuss a series of accessibility case studies in the Helsinki metropolitan area. Through temporal distance profiles and map visualizations, we show how each of the suggested measures can be useful depending on the focus of the analysis – each measure provides a different perspective on accessibility. Finally, we perform an all-to-all analysis between the 7463 PT stops in the Helsinki