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Navigability assessment of large-scale redesigns in nine public transport networks: Open timetable data approach

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ABSTRACT

Redesigns of public transport networks are complex undertakings requiring a careful balancing of several conflicting perspectives (e.g., user requirements vs system performance) and aims (e.g., increasing spatial coverage, increasing frequency). Current assessment tools omit an explicit focus on navigability, often identified as a key aspect of the user perspective. For understanding the multidimensional perspective of navigability, this research introduces an assessment framework with both system and journey-level measures. The system-level measures provide an overview of redesigns based on static network representations. The journey-level measures are based on journey trajectories generated with a customized routing algorithm, assessing the distributive effects of the redesign. The framework is applied to public transport networks from nine cities with recently implemented redesigns, namely Amsterdam, Auckland, Austin, Baltimore, Columbus, Helsinki, Houston, Indianapolis, and Wellington. Results indicate that the redesigns have improved navigability both from a system-level and user perspective in general. However, in some cases, improvements in navigability come at the cost of increased travel time and number of transfers. Furthermore, the results suggest that the redesigns have differing emphasis within the regions, for different times of day, and for different aspects of network structure. The results are discussed both from the perspective of the case findings and for drawing more general planning and policy recommendations. Finally, this research provides a basis for further transdisciplinary approaches, encouraging connections between transport modeling and complex networks approaches.

1. Introduction

Large changes in demand patterns, the need for regaining lost ridership, or enabling opportunities for urban growth are some of the reasons why cities redesign their public transport network (PTN) (Boisjoly et al., 2018; Nielsen et al., 2005; Walker, 2011). Such PTN service transformations can involve additions of transport modes, upgrades to a higher right-of-way, as well as changes in spatial (e.g., route alignment, station location) or temporal structure (e.g., shortening headways, extending service hours). Examples of implemented PTN redesigns include Santiago de Chile (Muñoz et al., 2009), Barcelona (Badia et al., 2017), Helsinki (Weckström et al., 2019), Jönköping (Nielsen and Lange, 2007), Melbourne (Currie and Tivendale, 2010), Portland, and others (Thompson and Brown, 2012). As funding for PTN redesigns usually comes from constrained public sources, their planning in practice requires a careful trade-

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off between the system perspective and user requirements. Such practical trade-offs usually have to be made in the context of path dependence of the current PTN structure (Cats et al., 2020), and challenging institutional rationalities (Hrelja et al., 2017; Legacy et al., 2017; Lowe and Hall, 2019; Weckström and Mladenović, 2020).

Distributed effects of PTN changes casting light on equity challenges are rarely assessed in planning practice, even if we know that different travel times and transfers that users experience around the city shape PT usability (Curtis et al., 2019; Karner, 2018; Weckström et al., 2019; El-Geneidy et al., 2016). Such PTN factors, as travel time and the number of transfers, impact usability in a subjective manner, as individuals have varying needs and capabilities across population and time. Despite this subjectivity, travel times and transfers are easily definable and measurable, and are therefore useful when assessing PTN redesigns from an accessibility equity perspective (Boisjoly and El-Geneidy, 2017). However, in addition to benefits, the redesigned PTN may impose many usability and travel experience challenges (Abenoza et al., 2017; van Lierop et al., 2018; Carrel and Walker, 2017). One aspect likely to impact PTN usability is navigability. Together with simpler fare systems, improved passenger information, and high frequencies, navigability is one of the aspects that are emphasized in modern PTN planning guidelines (Nielsen et al., 2005; McLeod et al., 2017; Mees, 2010; Weckström and Mladenović, 2020). For PTN to be usable, users need to have knowledge of the available services, or in the case of unfamiliar destinations, take more time to plan their trip. In particular, an easily navigable PTN requires less time and cognitive effort for route planning and route choice (Rüetschi and Timpf, 2005; Gallotti et al., 2016). In relation to immediate usability, navigability is essential in the long-term for developing a PT use habit (Kim et al., 2017).

From a user perspective, navigation in PTN happens on two levels: on the network level, by finding the correct combination of routes connecting the origin and destination, and as wayfinding, when navigating on access or transfer legs. In this context, there are several factors making PT route choice more challenging than for journeys using other modes. At the core of this challenge is the fact that PT trips are inherently multi-modal, as PT services typically do not offer a door-to-door service but involve access and transfers by walking or cycling. In addition, PTNs are not static networks such as roads, but are temporal networks, where connections between certain nodes only exist at a certain point in time, thus resulting in swift temporal variations in journey opportunities, and thus choices (Ortúzar and Willumsen, 2011; Weckström et al., 2019). Due to the multi-modality, the same challenges involving pathfinding in private modes apply to the wayfinding on access and transfers (Timpf, 2002; Rüetschi and Timpf, 2005). In contrast, navigation on the network level is hindered by factors decreasing network legibility such as the need to transfer and the presence of overlapping services (Rüetschi and Timpf, 2005). In addition to overlapping routes, people tend to be more aware of trunk routes or other routes with visible infrastructure (Dziekan, 2008). Finally, navigability aids such as maps, schedules, and route planners also shape the perception of the PTN (Raveau et al., 2014; Guo, 2011; Farag and Lyons, 2012; Hochmair, 2009).

Despite the acknowledged importance of navigability and existing knowledge of its behavioral underpinning, there is still a gap in PTN assessment frameworks that would account for both necessary trade-offs in planning practice and systematic ways of quantifying navigability. With this in mind, the aim of this research is the development of navigability assessment measures both for a system-level overview and detailed temporal-level analysis, building upon knowledge from transport modeling and complex networks. The proposed assessment framework is applied to navigability changes brought about by large-scale PTN redesigns in nine cities in the Global North, drawing implications for PTN planning. The outline of this paper is as follows. The next section will present a background on measuring PTN navigability from various modelling perspectives and elaborate on the research rationale. Section 3 describes the performance measures developed, while Section 4 describes redesign cases, the data used, as well as the performance measurement framework implemented. Results are presented in Section 5 which are discussed from an analytical perspective along with policy and planning perspectives in Section 6. Finally, conclusions and pathways for further research are outlined in Section 7.

2. Background

2.1. Modeling PTN navigability

This section summarizes previous research that provides a basis for developing an assessment framework involving temporal variations and a user-centered perspective of the PTN. Previous attempts to model the PTN navigability range in focus from a user perspective to a way of exploring network topology. Without an intent to summarize decades of research of user perspective in PTN modeling, we have to recognize that, navigability as finding and selecting a satisfying route between a set of origins and destinations, can be a complex undertaking (Dziekan, 2008; Ortúzar and Willumsen, 2011; Liu et al., 2010). In particular, PTN route choice as a part of PT traffic assignment has been studied extensively. The modern PTN route choice modelling is anchored in the behavioral perspective on the interaction between the PTN and its users, taking into account various travel factors such as travel time, transfers, monetary cost, comfort, and available information (Liu et al., 2010; Cats et al., 2020; Gentile and Noekel, 2016; Prato et al., 2012). For example, this strand of literature underlines the importance of associating the number of transfers with travel time for understanding route alternative utility. In recent years, efforts for developing more dynamic transit assignment modeling, combined with new data from smart cards and stated-preference surveys, have contributed to a higher level of understanding of users' PTN route choice (Liu et al., 2010; Nuzzolo and Comi, 2016). Furthermore, recent previous work simulating choice set generation in large-scale networks with multiple modes had provided additional understanding on assessing the quality of route choice sets for different user types (Rasmussen et al., 2016; Hoogendoorn-Lanser and Van Nes, 2004).

Looking specifically at PTN navigability measures, Timpf and Heye (2002) suggested measuring the complexity of transfer points and complete journey trajectories by combining measures describing the PTN and the street environment at transfer points. For the PTN, the in and out degrees of the node was used, while the environment was described by the number of street crossings and a dummy variable indicating if the boarding platform was visible from the alighting platform (Timpf and Heye, 2002). Woyciechowicz and

Shliselberg (2005) used a framework based on the spatial, procedural, and landmark knowledge defined by Lynch (1960) to measure navigability. Each type of knowledge was measured on a network level using a set of measures. The spatial knowledge dimension corresponds to ease of memorizing a part of the system as a cognitive map and then apply it to other parts of the system. This is measured through the repetitiveness of route patterns and how well the route hierarchy fits with the road hierarchy. In addition, the complexity of the PTN was measured through the number of routes. Procedural knowledge is related to travel paths through the city. Procedural knowledge was measured through the proportion of route trajectories on arterial roads and how split PT routes were because of one-way streets. Moreover, the continuity of the route with regards to road corridors was used as a measure. Lastly, landmark knowledge was described through a single indicator, measuring how well PT hubs were associated with commonly known urban landmarks.

In complex network research, the concept of navigability has been used to describe the complexity of finding a route between nodes in a network. Navigability measures have been used to characterize nodes, paths between nodes, or the whole network. Several approaches for measuring navigability in PTN's have been proposed, with the main difference in methodology being the assumption of users' knowledge about the network, as complete or incomplete. Cajueiro (2009) suggested navigability measurement using a hybrid measure that combined random and informed navigation. Information was given a value as a ratio of movement cost. This ratio at the critical point where random and informed navigation was at balance was used to characterize the network (Cajueiro, 2009). The same approach was used to characterize the stations of the London and Boston metro networks. The stations were characterized using hiding and access scores. The hiding score describes the ease to find the destination node starting from the other nodes, while the access score describes the ease to find the other nodes from the origin node (Cajueiro, 2010). Barberillo and Saldana (2010) measured the information required to encode the optimal path between stations in the Barcelona, Paris, New York, and Moscow metro networks, using the search information measure. The measure is based on the probability of selecting the correct route among all the available services on each station belonging to the path. Also here network-wide score as well as defining hide and access scores for stations were presented (Barberillo and Saldana, 2010). Gallotti et al. (2016) used a modified version of the search information measure. Unlike the original measure, here the possibility of multiple optimal paths does not affect the measure, as the PT user only needs to find one path. This research tried to simulate a situation where a PT journey is planned using a map. Furthermore, the methodology was anchored in the theory of the cognitive limits of humans. Using the methodology, the world's 15 largest metro systems were studied, including also multimodal networks of Paris, New York, and Tokyo. These were shown as being significantly more cognitively difficult to grasp compared to the metro networks alone.

As one of the additional efforts, Lee and Holme (2012) used a combination of greedy, random, and optimal routing to study railway networks among others. The greedy routing used the angle to the destination as a variable to decide which was the next step in the search. The greedy routing simulated the combination of limited local information to the complete lack of system-wide information about the optimal path. Navigability was defined as the ratio in distance (number of steps in the network) required by the greedy or random routing compared to the optimal path (Lee and Holme, 2012). De Domenico et al. (2014) used random walks to study the navigability of London's rail-based PT networks under random failures. The use of random walks was justified by the inherently incomplete knowledge of the partially failed system. Navigability is defined as coverage: the average number of distinct nodes reached within a time limit when assuming a random walk can start at any node (De Domenico et al., 2014). Finally, a few studies have explored the relationship between the diversity of journey alternatives and PTN robustness or vulnerability. As one of the examples of this research, Yang et al. (2017) used the average number of reasonable journey alternatives generated by Dial's stochastic loading algorithm between all origins and destinations as a measure for robustness. Stop vulnerability was measured as the change in average diversity if the stop in question was removed. Frappier et al. (2018) measured robustness between origin and destination by considering the independence of the trajectories of journey options. This was implemented by first calculating the independence level of the journey alternatives, by taking into account the length of sections overlapping with other journey alternatives and the number of overlapping journey alternatives. Diversity was then defined as the sum of the independence level of the journey alternatives.

2.2. Research rationale

From the above background, there are three areas for developing PTN navigability assessment in the context of redesigning PTNs. First, there is a need for moving beyond the assumption that PTN has a static network structure, with only specific PT modes available (e.g., analysis of a metro system in isolation from other urban PT modes, and as a static network). In contrast, the development of an assessment framework has to explicitly include temporal variations brought about by the schedule structure. As PTNs are inherently schedule-based systems, the available journey alternatives especially those involving transfers may change depending on the time of day, even minute to minute. Moreover, many urban PTNs include several modes and rights-of-way, which influence navigability. While having choices is generally considered as positive, choice overload may have many negative impacts such as decision avoidance (Schwartz and Ward, 2004; Schwartz, 2004). The decision avoidance between journey alternatives may nudge persons away from public transport. Second, there is a need for moving beyond the assumption that users move in PTN with a random movement, as often assumed in complex networks models. In contrast, deeper user understanding requires the development of an assessment framework that accounts for existing knowledge of user route choice. Specifically, PT users do not move randomly, as they are often well aware or at least have the opportunity to find out about their travel options. Third, there is a need to move towards assessment frameworks that are useful for explicitly dealing with trade-offs inherent in PTN planning practice, while also being computationally usable. Such a trade-off requires finding a fine balance between the model's capability in representing reality, and the model's simplicity, for straightforward implementation (Silva et al., 2017; Boisjoly and El-Geneidy, 2017). Thus, on the one hand, the formulation of the assessment framework has to go beyond focusing on describing PTN topology in general terms. For improving the model's capability, we need to account that the navigability that a PT user experiences does not solely lie in the PTN topology, but in the journey options that are available for desired origin–destination pairs. On the other hand, usefulness for planning practice requires accounting for limiting data requirements, as well as keeping application procedures understandable and transparent. The last point about transparency relates to the use of open data, which has been recognized as one of the major opportunities for developing PTN planning methods (Davidsson et al., 2016; Kujala et al., 2018a).

3. Methodology

Here, we elaborate on the formulation of performance measures used to describe the changes brought about by the PTN redesigns in general and the navigability changes in particular.

3.1. System-level static network measures

The measures in this section are based on a static network representation of the PTN within a specific time window. The stops are represented as nodes, while an available PTN service to the next node forms a directed edge with a geographic length. This is commonly called space L topology (Sienkiewicz and Hołyst, 2005). Public transport is traditionally based on fixed routes (or lines) making it easier to convey the service. However, this is often a simplification of the actual service structure, in which routes typically consists of bidirectional service and sometimes include scheduled inconsistencies in stopping pattern, for example, to adapt to different demand levels or to provide service on depot trips. To take into account the inconsistencies that can be present in routes, route variants based on individual trips are used instead. The schedule of a route consists of trips forming time-dependent sequences of stops. Ignoring the time dependency, the trips using the same sequence of stops are lumped together, forming route variants. Route variants have a given service frequency depending on the number of initial trips and a length based on the sum of all edge lengths in the sequence.

The *Number of route variants* measure, which is calculated as a simple count of route variants, gives a straightforward approximation of the PTN complexity. *Average route overlap* describes the network structure, through the presence of overlapping routes. The measure is adapted from Derrible and Kennedy (2011) and calculated as:

$$\lambda = \frac{\sum_i R_i}{R}, \tag{1}$$

where R is the sum of all edge lengths and R_i the length of route variant i. *Average frequency* F is calculated on a similar basis, however, with route variant frequency f_i as weight. In effect, this results in the sum $\sum_i f_i R_i$, the service kilometrage (vehicle kilometers per unit of time), in the numerator. *Average frequency* is thus calculated as

$$F = \frac{\sum_i f_i R_i}{R}. \tag{2}$$

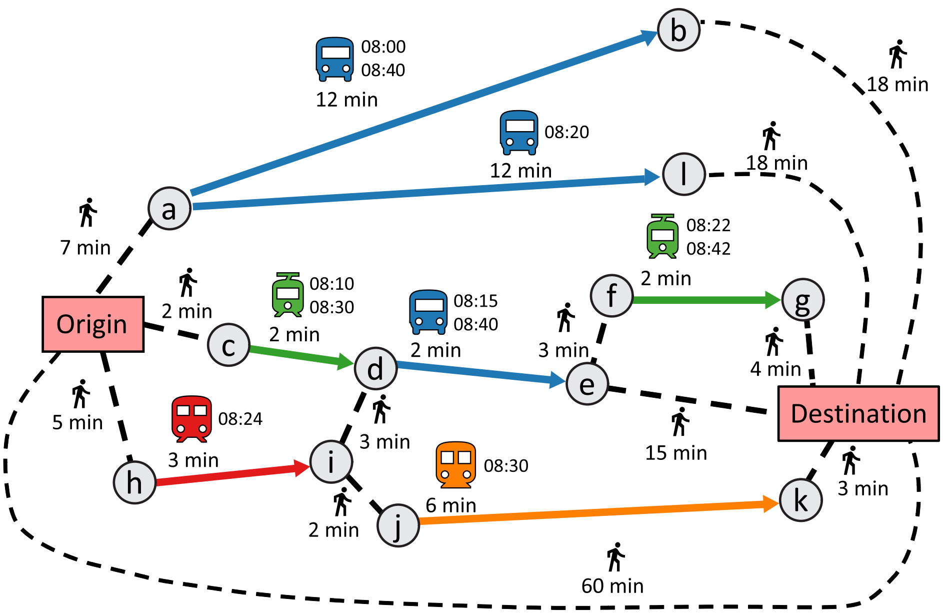

Fig. 1. PT services between an origin–destination pair. The figure is adapted and modified from Kujala et al. (2018b). The icons for different travel modes are adapted from Google's Material Design icon collection (https://material.io/icons/), licensed under Apache Lice.nse version 2.0.

Table 1
All journey alternatives between the origin–destination pair of Fig. 1.

Journey alternative v_i	Complete trajectory	Unique trajectory	Trajectory variant V_j	t_{dep}	t_{arr}	b	Pareto-optimal	$\tau_{generalized}$(min)	t'_{arr}	Generalized fastest-path	pwt_{fp}(min)
A*	Oa(b) D	a	1	07:53	08:30	1	×	40	08:33	×	–
B	Ocd(e) f(g) D	cdf	2	08:08	08:28	3	×	29	08:37	×	8
C	Ocd(e) D	cd	3	08:08	08:32	2	×	30	08:38		–
D	Ocd(e) D	cd	3	08:08	08:57	2		55	09:03		–
E	Oa(l) D	a	1	08:13	08:50	1	×	40	08:53		-
F	Oh(i) j(k) D	hj	4	08:19	08:39	2	×	26	08:45	×	11
G	Oh(i) d(e) D	hd	5	08:19	08:57	2		44	09:03		–
H	Ocd(e) D	cd	3	08:28	08:57	2	×	35	09:03	×	9
I**	Oa(b) D	a	1	08:33	09:10	1	×	40	09:13	×	2

This measure gives some indication of the level of service offered in the PTN on average. However, to give a more complete indication of the service offered, this is complemented with the *High-frequency service prevalence* measure $H_{f\geqslant f_t}$, that describes the relative proportion of the route variants with frequent service, that is the proportion of service kilometrage produced by the frequent routes, calculated as

$$H_{f\geqslant f_t} = \frac{\sum_i f_i R_i [f \geqslant f_t]}{\sum_i f_i R_i}. \tag{3}$$

The equation is limited by the frequency threshold f_t, set to 4 trips per hour. *Weighted mean service hours S* is defined as

$$S = \frac{\sum_i s_i f_i R_i}{\sum_i f_i R_i}, \tag{4}$$

where s_i is the count of daily hours (X:00 - X:59) in which route variant i has scheduled service. The service hours are weighted by service kilometrage. The measure describes the similarity of the PTN during the day. A high value indicates that the same route variants operate most of the day, thus making it easier to memorize the offered service.

3.2. Pareto-optimal journey alternatives and journey trajectories

For developing journey-level measures, in contrast to the previous works on PTN navigability, this research applies a temporal network approach. The temporal network takes into account the scheduled services in addition to the topography of the network. The routing algorithm based on the Connection Scan Algorithm (CSA) identifies the journey alternatives that are Pareto-optimal with regards to departure time (later better), arrival time (earlier better), and transfers (lower better) within the desired analysis time window (Kujala et al., 2018b). These sets of journey alternatives are the fastest travel options at all points of time when using a desired maximum number of transfers. We will explore the concept using Fig. 1 showing a set of transportation options forming a network between the origin and destination. PT stops are designated as circles with letters for easier identification. Connections between stops are given a travel time, with PT modes also given a direction of travel and scheduled departure times. In the accompanying Table 1, the output of the routing process is presented, with each row representing one journey alternative v_i. The example uses an analysis time window ranging from $t_{start} = 8{:}00$ to $t_{end} = 8{:}30$, meaning that departure times t_{dep} needs to be in this range for inclusion. This excludes alternatives A and I from the analysis. However, the first journey immediately after the analysis time window I is used to represent the time after the last accepted trip and the end of the analysis time window (t_{end}) in measures using time as weight. The column labeled "Pareto-optimal" indicates whether the journey is Pareto-optimal if all three journey features ($t_{\mathrm{dep}}, t_{\mathrm{arr}}$ and b) are considered.

To define a set of journey alternatives where the next optimal journey alternative in all cases is explicit, the transfers (number of vehicle boardings) are given a weight, and the Pareto-optimality is determined again using t_{dep} and the generalized arrival time t_{arr}'. The generalized travel time $\tau_{generalized}$ is calculated as:

$$\tau_{generalized} = t_{arr} - t_{dep} + kb, \tag{5}$$

where k is a transfer penalty and b the number of vehicle boardings. For instance, if $k = 0$ this Pareto-optimal set of journeys would contain the fastest-paths. However, to avoid journeys with an extensive number of transfers, where avoidable, a transfer penalty of 3 min is applied to generate the Pareto-optimal journey set based on generalized travel time. The resulting set of journeys are indicated by the *Generalized fastest-path* column.

The routing process stores journey trajectories as these are the basis of the navigability measures. To achieve consistency in cases where multiple transfer locations are possible without changing the overall travel time, the route alternative that maximizes the transfer margin is selected in the routing process. The *complete trajectory* column indicates the order of PT stops on the path from the origin O to the destination D. The *unique trajectory* column shows the stop sequence that determines the uniqueness of the trajectory variant V_j. The uniqueness of journey trajectories is defined based on the stops where a PT vehicle is boarded, in addition to the origin and destination stops. This approach was selected because it best describing the trajectory choice from a PT user perspective. The PT user can wait for a bus or a train on only one stop at a time, therefore the boarding stops are important for the route trajectory. The intermediate stops lack importance in defining the journey trajectory as these are depending on the choice of route. The PT user needs to know when to alight the vehicle but does not need to consider all the intermediate stops separately. Furthermore, the alighting stops at the destination or in the case of a transfer connection were not considered defining the uniqueness of a journey trajectory as these are highly dependent on the destination point or following boarding stop respectively.

3.3. Measuring navigability on a journey-level

Based on the set of Pareto-optimal set of journey alternatives and their trajectories, a set of performance measures describing navigability from a journey-level perspective can be calculated. Contrary to previous simplified navigability measures, here the diversity of the available travel options is used as a proxy for navigability. With this in mind, the measures presented here are working on the premise that the PT user is familiar with the journey alternatives and instead the navigability challenge is based on the difficulty of knowing which alternative to take at a specific time. This is in contrast to previous measures that focus on measuring the complexity of the journey itself, for example by wayfinding at transfer points. Here, we focus only on travel time and transfers and do not include other decision domains (e.g., choosing departure time for certain trips or choosing housing location in relation to PTN structure). The journey alternatives ($v_i, i \in \{1,2,\dots N\}$) are defined through the trajectory (v_i), arrival and departure times, and the number of transfers. A set of journeys with the same trajectory are called a trajectory variant ($V_j \ni \{i\dots\}$). The trajectory variants have an associated frequency based on the number of journey alternatives $f_{V_j} = |V_j|$.

The overall availability of services between two locations can be described through the *Number of Pareto-optimal journey alternatives* (*N*). However, this value does not reveal if there are any variations in the optimal route. The *Number of trajectory variants* (*V*) is better suited for measuring complexity. This value is defined based on the number of unique journey trajectories of Pareto-optimal journey alternatives. While a multitude of trajectory variants may imply complexity, we can also consider the possibility of there being a single route variant of the Pareto-optimal journeys, that alone provides satisfactory service. The *Frequency of most frequent trajectory variant* is defined as,

$$f_{V_{max}} = max(f_{V_j}). \tag{6}$$

When considering other Pareto-criteria besides travel time, it is possible to assess the user perspective associated with understanding the choice set of the available journey alternatives as the *Proportion of generalized fastest-path journeys*. The assumption from the user perspective is that, for example, choosing between the shortest-time alternative and the alternative not requiring transfers is cognitively more demanding than a case where there is only one alternative available, which fulfills both criteria. The measure is calculated as:

$$P_{fp} = N_{fp}/N. \tag{7}$$

where N_{fp} is the number of fastest path journeys. Considering a specific PT user profile, by giving a weight to transfers, the travel time and transfers can be combined into a single value, i.e., generalized travel time. When defining the Pareto-optimal set of journeys for this PT user profile, we need to consider only the generalized travel time and the departure time. This new set of journey alternatives differ from the initial journey set in that each of the journey alternatives *i* has an associated time span before the departure, pre-journey waiting time pwt_i, in which no other journey departs. In our example from Fig. 1, journeys B, F, H, and I are Pareto-optimal, when considering a transfer penalty of 3 min per transfer. This set of journeys has unique departure times, forming a sequence of non-overlapping events and therefore having definable pre-journey waiting time. This was not the case for the initial set of Pareto-optimal journeys considering transfers separately, due to the journey alternatives B and C having the same departure time. Pre-journey waiting time is calculated as follows:

$$\begin{cases} pwt_i = t_{dep_i} - t_{start}, \text{IF} t_{start} > t_{dep_{i-1}} \\ pwt_i = t_{end} - t_{dep_{i-1}}, \text{IF} t_{end} < t_{dep_i} \\ pwt_i = t_{dep_i} - t_{dep_{i-1}} \end{cases} \tag{8}$$

The pwt_i for the generalized fastest-path journey alternatives of the example case are shown in Table 1. To quantify the time in which the journey alternative is a valid alternative the user can consider (i.e. the alternative has not departed, and there are no other options before it), we relate the pre-journey waiting time to the duration of the analysis window $T = t_{end} - t_{start}$. Thus, we calculate the prevalence P_j as a fraction of the analysis window:

$$P_j = \frac{\sum pwt_i}{T}, i \in V_j. \tag{9}$$

The following measures, based on prevalence P_j, thus only considers the generalized fastest paths, not all Pareto-optimal journeys. The *Probability of the most prevalent trajectory variant* is calculated as the maximum of P_j:

$$P_{j_{max}} = \max(P_j). \tag{10}$$

From a PT user perspective, this measure describes the probability of choosing the optimal route option, given correct knowledge of the journey path that is optimal most frequently. A variation of this measure is given by considering the *Probability of the most prevalent first boarding stop*.

$$P_{s_{max}} = \max(P_s), s \in [0, 1, 2, \ldots S], \tag{11}$$

where s are the initial stops of journey alternatives V_j. From a PT user perspective, this measure describes the probability of selecting the optimal route option given that the departure stop with the most prevailing journey alternative is known. The first boarding stop is defined as the stop where the passenger first accesses a PT vehicle. Here, the first boarding stop is seen as creating a lock-in limiting the available journey alternatives. At this stop, the PT user can still select any of the available trajectory variants that pass through the stop. Therefore, it always holds true that $P_{smax} \geqslant P_{jmax}$. The *Diversity of journey alternatives* is calculated as Simpson's diversity index (Simpson, 1949):

$$D = \sum_{j=0}^{V} P_j^2. \tag{12}$$

The above measure describes the probability that two journeys departing at a random time point within the analysis window follow the same trajectory. From a PT user perspective, multiplication can be pictured as occurrences of two consecutive days. A low value of D implies a high diversity.

To help understand the calculations of the values shown in Table 1, we use journey alternative F as an example. Journey F consists of the following journey legs:

- O-h: 5-min walk
- h-i: 3-min train ride at 08:24
- i-j: 2-min walk
- j: 1-min wait
- j-k: 6-min metro ride at 08:30
- k-D 3-min walk

To match the train departure time, $t_{dep} = 08{:}24–0{:}05 = 08{:}19$. We also find that the arrival time is $t_{arr} = t_{dep} + 0{:}05 + 0{:}03 + 0{:}02 + 0{:}01 + 0{:}06 + 0{:}03 = 08{:}39$. The generalized travel time can then be calculated as $\tau_{generalized} = 08{:}39–08{:}19 + 3$ min/boarding * 2 boardings = 26 min, yielding $t_{arr}' = 08{:}19 + 26$ min $= 08{:}45$. Since we find that $t_{start} > t_{dep_{i-1}} \equiv 08{:}00 > 08{:}08$ and $t_{end} < t_{dep_i} \equiv 08{:}30 < 08{:}19$ are both false, the pre-journey waiting time is calculated as $pwt_i = t_{dep_i} - t_{dep_{i-1}} = 08{:}19–08{:}08 = 11$. Similarly, pwt_i values for other alternatives in the set are respectively 8, 9, and 2 min for B, H, and I. The measures of journey diversity for the example case of Table 1 results in the following values:

- *Number of Pareto-optimal journey alternatives*, $N = 6$
- *Number of trajectory variants*, $V = 4$
- *Frequency of most frequent trajectory variant*, $f_{V_{max}} = 2$
- *Prevelance P_j for the journey alternatives are calculated as:* $P_4 = 11/30, P_2 = 8/30, P_3 = 9/30 \text{and} P_1 = 2/30$
- *Probability of the most prevalent trajectory variant*, $P_{j_{max}} = 11min/30min = 0.367$
- *Probability of the most prevalent first boarding stop*, $P_{s_{max}} = 17min/30min = 0.567$
- *Diversity of journey alternatives*, $D = (8/30)^2 + (11/30)^2 + (9/30)^2 + (2/30)^2 = 0.300$
- *Proportion fastest-path journeys*, $P_{fp} = 4/6 = 0.667$

3.4. Journey-level destination sampling

Routing is performed in all-to-many manner, from all stops as origins to a set of sampled destination stops. A sampling of destination stops is implemented due to the need to balance comprehensiveness and computing effort for a modeling methodology. The choice between how many stops to include in the modelling approach varies between a handful of stops to all the stops. With the increase in the number of stops, one can assume that modeling approach is better accounting for the full extent of PTN reality. However, the increase in comprehensiveness also increases computing efforts. Thus, sampling is used as a way to balance this inherent modeling trade-off. On the one hand, for deciding on the sampling need and approach, the aim was to move away from focusing only on a handful of origin–destination pairs for assessment, especially only those in the city center, as often used in accessibility modeling (Weckström et al., 2019). A very limited number of stops does not provide a good enough representation of the whole region and related PTN in question. For example, an analysis of broader benefits and burdens from PTN redesign has to include a combination of stop types, such as stops on the trunk sections and stops further away from the trunk section. On the other hand, the computational time depends mainly on the number of stops and events in the network, and the computing hardware used. Here, one has to recognize that analysis of all origin–destination pairs of stops would prolong computational time, and would also impose higher requirements on computational equipment, often not available in PTN planning processes. As an intermediate approach, the choice of sampling relied on experiences from the commonly used approach of tessellations with corresponding centroids (Foth et al., 2013; Farber and Fu, 2017; Tenkanen and Toivonen, 2020). However, for the scope of this research, grid-based sampling should also be useful to link to the PTN structure changes. In particular, stops directly correspond to PTN routes, but are also not distributed in a uniformly random manner across the city, but follow built environment form. In fact, the probability of finding a PT stop in space declines with the number of stops in the cell, as stops are relatively close by in space, if there are any in a certain urban area. In addition, for the routing algorithm used, it is necessary to record the measures for all stops during the routing process. A set of fewer origin points would thus not make the routing process run faster, but merely lose data that has already been calculated. For implementation, the destination stops are selected as a spatially stratified sample using a grid tessellation, with 5000-meter * 5000-meter cells. For each cell, a random set of destination stops is drawn. The size of the set is proportional to the total number of stops in the cell. If the number of stops in the cell is low, it is possible that the cell will not have any stops included. The measures describing a single origin are aggregated by calculating the mean for each corresponding origin–destination pair. Origin–destination pairs with no valid journey alternatives are excluded from further calculations. As a result of this sampling in the nine case cities, the sample consists of the journey alternatives between origins and destination stops where all stops are used as origins, while one-tenth of the total number of stops are destinations. For evaluating the sampling procedure, the confidence intervals were calculated using bootstrapping (Efron, 1979). Finally, a typical processing time on a modern computer is roughly two to five minutes. This time includes routing and the post-processing of the journey alternatives into measures for the cities of this paper between all stops to one destination stop. Such computational times are considered reasonable given the fact that PTN redesign processes can last for several months or years, thus allowing the planner to run even several iterations during the course of one day.

4. Case implementation

This section presents the performance measurement framework implemented to analyze PTN redesigns in the set of nine cities, and an overview of the data and the included nine cities.

4.1. Performance measurement framework

Given a) the temporality of PTN and associated challenges that users face in making choices, b) the need for more realistic representations of those user decisions, as well as c) the need for useful frameworks for planning practice, these aspects require a careful trade-off in establishing performance indicators. The first set of proposed indicators bases on a static network representation, using stop-to-stop network segments and the unique route variants as starting points (Fig. 2). These measures focus on the macroscopic changes of the network and should be the easiest to compute for PTN redesign. The second set of proposed measures bases on the variations in Pareto-optimal journey options calculated using routing over the morning peak period, thus emphasizing PTN temporality and user decisions. With these two levels, the multi-measure approach was chosen to reflect the different perspectives of system-level performance (i.e., the network as a whole) and user-level perspectives (i.e., journeys made in the network). Furthermore, the use of multiple indicators attempts to account for different user types and preferences (e.g. shifting in usage frequency and familiarity). Moreover, to facilitate the assessment of distributive effects, both the overall and spatial distributions of effects are included in the analysis. Following the principles of open science, the scripts used for implementing this framework are released online (https://github.com/jweckstr/journey-diversity-scripts).

4.2. PTN redesign cases and data

The methodology is applied to nine case PTN redesigns (Table 2). The cases were selected based on three criteria. First, the PTN redesign needs to be a more notable change in the PTN than yearly or seasonal schedule changes. A PTN redesign can be a complete network overhaul or a partial redesign, e.g. in the case of adding a new mode or expanding frequent service. The aim was to find a range of redesigns varying in scope, both related to the size of the PTN and in absolute terms. Second, the inclusion of cities was limited to PTNs with a somewhat limited spatial extent where most of the PTN can be accessed within the 180 min travel time budget. Lastly, the schedule data needs to be freely available both for the time before and after the redesign for the analysis to be possible. The calculations are based on the General Transit Feed Specification (GTFS) format. Furthermore, OpenStreetMap (OSM) data was used for walking routing. The whole data processing, from converting GTFS feeds into databases to calculating performance measures, was performed using the gtfspy package (https://github.com/CxAalto/gtfspy) implemented in Python programming language (Weckström et al., 2019; Kujala et al., 2018a; Kujala et al., 2018b). To give an idea of the extent of the changes in each case, Fig. 3 shows the general geography of each city and PTN structure before and after the redesign. Maps highlight four different route categories, namely radial, cross, orbital, and the feeder route. Categories are determined based on the city center (area with the largest concentration of PT service in terms of frequency). Radials terminate within this area, while cross-routes pass through it. Feeders and orbitals are differentiated based on the sector served outside the city center. Routes highlighted on the map are those with service frequency equal to or higher than 4 vehicles per hour. In the corner of each map, there is an additional graph showing frequency distribution per route type. These figures highlight additions and removals of specific types of routes and their alignments based on trunk-feeder or other network redesign aspects. As some radial or cross routes have been focused on as trunk lines, one can also see an increase in the feeder and orbital routes at several locations. Moreover, several cities have an increase in the coverage area for PT routes after the redesign. Finally, frequency distribution graphs show changes in vehicle operation kilometers, indicating changes in frequency and resources.

5. Results

This section presents the changes brought about by the PTN redesigns using two approaches. In Section 5.1 the characteristics of the redesign are presented, using static network measures. Section 5.2 tries to quantify the impacts of the redesigns on PTN using level-of-service and navigability measures based on Pareto-optimal routing. However, for the sake of brevity, results for only one routing-based navigability measure are presented.

5.1. System-level changes of public transport networks

To provide a background for the changes in navigability, the characteristics of the PTN and the implemented changes are quantified. To this end, we use a selection of performance measures to describe the initial and transformed state of the PTN networks (Fig. 4). While the focus areas of change differ between cities, the direction of change for each measure seems to be similar for almost every city. Based on the performance measures, the European and New Zealand cities have higher Average segment frequency than the American counterparts, indicating a higher service level. The PTNs of the American cities, with orthogonal street grids, and Amsterdam with an emphasis on rail-based PT modes, rely on average on fewer routes on each network segment. In contrast, the initial states of Auckland's and Helsinki's PTN's are characterized by high route overlap, while the redesigned networks have brought these cities closer to their peers. All cities, although in particular Houston, Baltimore, and Auckland increased the service hours of their routes. Furthermore, the mentioned cities along with Austin and Helsinki focused more than initially on routes that run with 15-min headways or less. When considering the profiles based on the measures, the changes for Auckland seems to be the most radical, while the system of Amsterdam only experienced minor changes.

5.2. Journey-level changes of public transport networks

This section presents the findings unraveled using the routing based measures. Fig. 5–7 show the distribution of travel times, number of transfers, and navigability (diversity of journey alternatives). Both distributions before and after the PTN redesign are shown (panel A) along with the distribution of change (panel B) in the respective figure. There are clear differences in the distributions of travel time, with Amsterdam, Auckland, and Houston having a greater range than the other cities. It is worth noting, however, that the travel time distribution is highly dependent on the size of the PTN. The PTN of Amsterdam covers the largest area, including surrounding rural areas and neighboring towns. The median of average journey speeds in Amsterdam is, however, the fastest at 25 km/h. The median speeds in Helsinki are 23 km/h, with the other cities having median speeds between 14 and 20 km/h. Generally, the ranges of travel times correspond well with the distribution of transfers, with Helsinki being an exception with relatively short travel times but a high reliance on transfers. The transfer distributions are heavily concentrated around integer values in all cities. However, the degree of values between the integer points seems to vary slightly between PTNs with Auckland, Helsinki, Houston, and Wellington having more origin–destination pairs with the number of transfers being between integers. This indicates not only altering routes but also changes in the number of transfers. For Auckland there seems to be a shift towards the integer points, indicating structural changes in the PTN. The distribution of change for all cities range from positive to negative. Houston stands out as a city where the median travel times have increased which can be linked to the slight increase in the reliance on transfers (Fig. 6 panel B). However, the link between changes in transfers and travel time is missing for Auckland. Austin and Wellington show slight travel time gains, with the median of most of the cities' travel times remaining constant. Auckland and Helsinki perform poorly in navigability (Fig. 7, panel A). However, Auckland is among the cities with the largest improvements in navigability along with Austin. In many, the overall distribution of navigability experienced only minor changes. This was the case especially if the redesign was small in relation to the overall size of the network, such as the case with Amsterdam and Indianapolis.

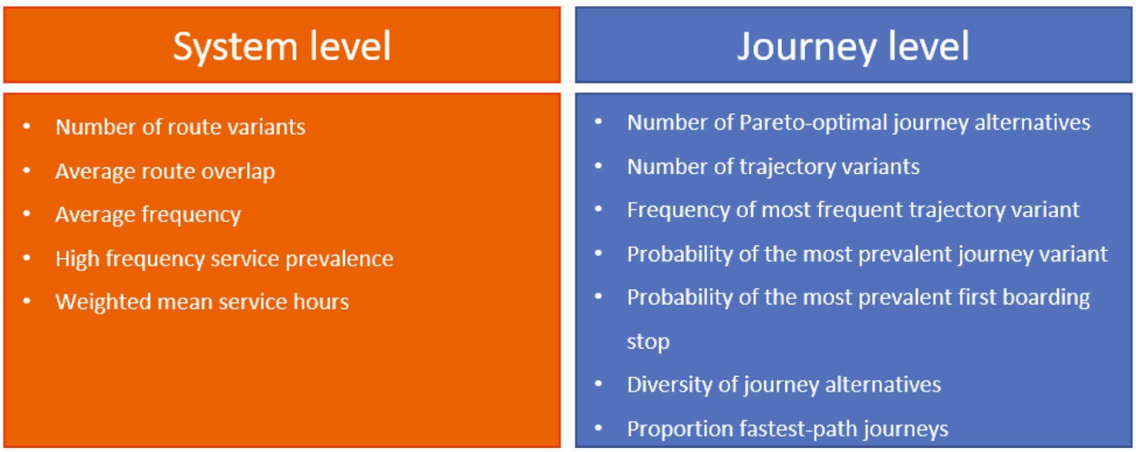

Fig. 2. Performance measurement framework.

Table 2
Overview of included GTFS feeds.

City	Years	Feed validity	Type of redesign
Amsterdam	2017	Oct 9 – Oct 15	Metro extension, partial tram and bus network
	2018	Oct 8 – Oct 14	
Auckland	2016	Mar 7 – Mar 13	Bus network
	2018	Nov 5 – Nov 11	
Austin	2017	Oct 30 – Nov 5	Bus network
	2018	Oct 15 – Oct 21	
Baltimore	2017	Mar 13 – Mar 19	Bus network
	2018	Mar 12 – Mar 18	
Columbus	2017	Mar 20 – Mar 26	Bus network
	2018	Mar 5 – Mar 11	
Helsinki	2014	Oct 6 – Oct 12	Metro and commuter train extension, partial bus and tram network
	2018	Nov 19 – Nov 25	
Houston	2015	Mar 30 – Apr 5	Light rail extension, bus network
	2018	Apr 2 – Apr 8	
Indianapolis	2016	Sep 12 – Sep 18	New trunk bus route
	2019	Sep 9 – Sep 15	
Wellington	2017	Sep 18 – Sep 24	Bus network
	2018	Oct 8 – Oct 14	

The Fig. 8 shows the spatial distribution of change in the average diversity of journey alternatives within the cities. Keeping in mind the scale of the *diversity of journey alternatives* measure, ranging from 1 completely uniform to 0 completely diverse, the red points highlight stops with a more uniform set of journey alternatives, suggesting improved navigability. On the contrary, blue points indicate stops with added diversity and decreased navigability. Similarly to Fig. 7, the cities show mostly positive outcomes. As previously, Amsterdam and Indianapolis show only minor changes, with positive and negative changes in a roughly equal number of stops. In Helsinki, Auckland, and Austin the changes seem to be more clearly clustered into larger continuous areas, while for the other networks it is common that the stronger changes are clustered into specific streets or intersections. Looking at further details within a city, the areas impacted by the heavy rail investments in the western area are clearly visible in Helsinki, with a positive impact on navigability. A similar effect can be seen on the southernmost stretch of Indianapolis' new Red Line, a new BRT cross-city north–south route spanning from Broad Ripple to the University of Indianapolis. In contrast, Amsterdam's North–South metro line seems to have a negative impact on PT navigability in the northern areas that previously relied exclusively on buses. Finally, due to the large sample sizes ranging from 0.3 to 3 million origin–destination pairs, the estimated bias found is negligible, $\pm$ 6 s of travel time, $\pm$ 0.003 transfers, and $\pm$ 0.001 for the diversity of journey alternatives on 95 percent confidence level.

6. Discussion

6.1. *PTN redesign impacts on navigability*

As indicated by Figs. 3 and 4 the scope of the network redesigns have several similarities despite being in different urban contexts. Overall, the results indicate that the redesigns have improved navigability both from a system-level and user perspective. Regarding redesign actions, first, there has been a general increase in the number of higher frequency routes. All of the cities have developed their frequent bus network either by consolidating infrequent routes into fewer frequent ones or by redistributing resources from less used routes. In some cities, this has happened in conjunction with investments in rail-based modes (see Table 2). Second, there is an increased focus on orbital journeys with new routes and higher frequencies, often connecting different trunk sections. In a few cities, namely Auckland, Helsinki, and Houston, there is also a shift from trunk-branch towards trunk-feeder systems (Weckström et al., 2019). Through the aforementioned actions, the redesigns have brought a stronger hierarchical structure into the PTNs. Instead of providing a large number of direct, infrequent routes with consequently high route overlap, the redesigned PTNs tend to rely more on transfers. While all the cities surveyed in this research showed at least some indications of moving towards a more hierarchical network structure, many also focused on improving off-peak service and lengthening service hours in general as indicated by *Frequent network proportion (day)* and *Weighted mean service hours* measures respectively (Fig. 4). In doing this, navigability, when defined as the diversity of journey alternatives, has also generally improved. In particular, the cities with the clearest changes on the network level (Fig. 4), are showing decreases in the diversity of journey alternatives. For example, the consolidation of low-frequency routes into higher frequency ones also consolidates the number of trajectory variants. In addition, on the basis of the results presented here, it seems as the key principles of a navigable network are minimizing route overlap and creating a frequent and quick trunk network as the PTN backbone. Moreover, it can also be argued that a combination of marginal gains in navigability and increases in peak-hour travel time in some cities could have been a result of shifting resources to the off-peak periods.

Looking further at specific examples from Figs. 4 and 8, one can highlight the cases of Helsinki and Amsterdam, which both had metro extensions and partial overhauls of the on-street modes. However, the results indicate that the outcomes of these redesign actions are different in the two respective contexts. The whole West Metro corridor in the Helsinki region saw a reduction in the diversity of journey alternatives, while the extension to Amsterdam-Noord saw an opposite effect where diversity of journey alternatives increased, indicated by around 0.3 and −0.2 units of change respectively (Fig. 8). From Fig. 4, one can conclude that

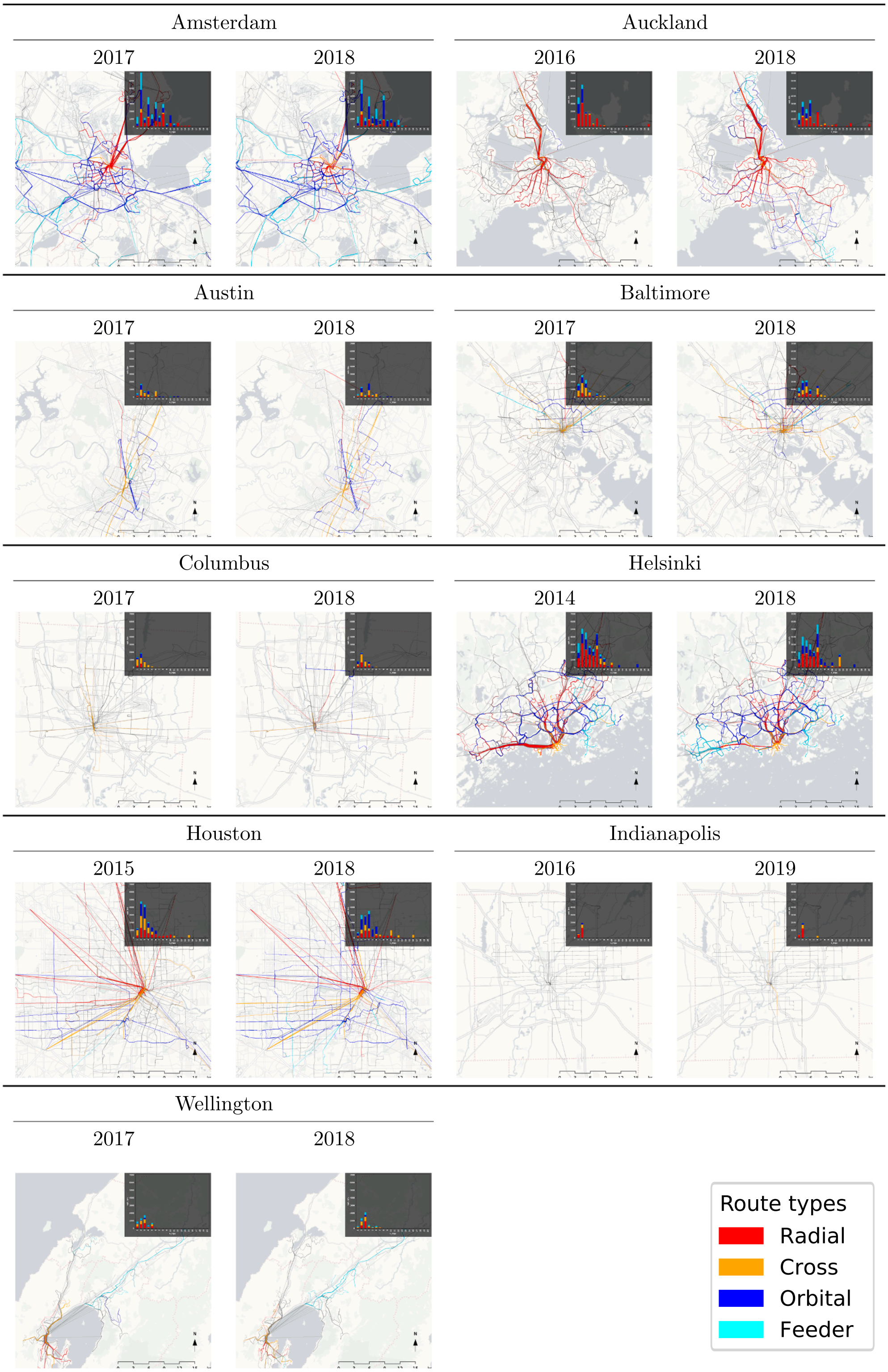

Fig. 3. Public transport networks by route category before and after the redesign, with the corresponding frequency distribution. Only routes with service frequency of minimum 4 trips per hour highlighted on the maps. Background map (c) OpenStreetMap contributors, (c) Carto.

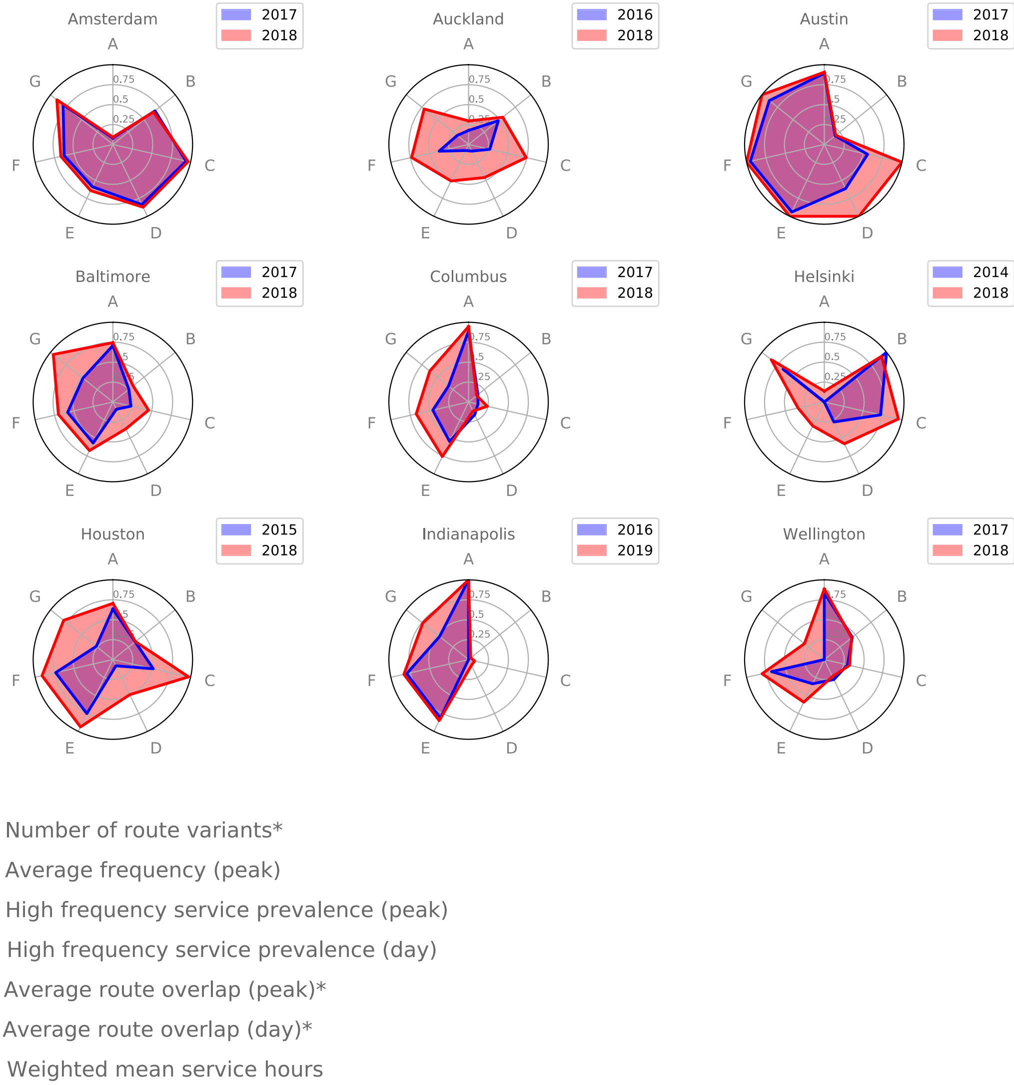

Fig. 4. The effect of the redesign on a selection of PTN measures. The measures are normalized on a scale from 0 to 1. Reversed axis indicated with *.

Amsterdam only showed minor changes in all categories, while the network of Helsinki saw a clear transition towards a similar profile as Amsterdam. This example underlines that the complexity that a PT user experience is not mainly about overall PTN topology, but about journey options available for desired origin–destination pairs. Thus, we can observe strong emergence aspects, often highlighted by complex systems theory. While the system level indicators in Fig. 4 often give an accurate direction of change, the outcomes can be thoroughly assessed only using journey-level indicators. Thus, navigability emerges from a multitude of interrelated factors such as route alignments, frequency, the synchronicity between routes, service speed, and the walking infrastructure. Due to these complex interrelations, it is difficult to establish an explicit causal relationship between the PTN and the navigability outcomes on a nodal basis.

In relation to the methodology and the research setup, there are several limitations that should be acknowledged, and we further reflect on them in relation to future research directions in the Conclusion section. First, we cannot claim that our modeling framework accounts for the full extent of diversity in human beings. For example, navigability relates to users' perceptions and abilities (e.g., cognitive workload), which are not the direct subject of study here. Furthermore, there are multiple criteria beyond travel time and transfers not accounted for in this research, that impact user decisions related to PT travel on a daily basis. Possible criteria to consider in the future include, the selection of departure time for certain trips, walking distances, and the reliability of service. Second, the selection of nine case cities required reductions in the depth of study per each case. Furthermore, the sample of nine PTN systems does not represent a full extent of cities around the globe, as it does not include all the city scales and contexts. These nine cities have been selected due to recent redesigns and curated data availability. Moreover, the analysis for each city does not account for PTN design at multiple points in time. Finally, the analysis framework, including the sampling procedure, does not establish straightforward causal relationships between the PTN on a system-level and the navigability outcomes measured on a nodal basis, as well as relationships

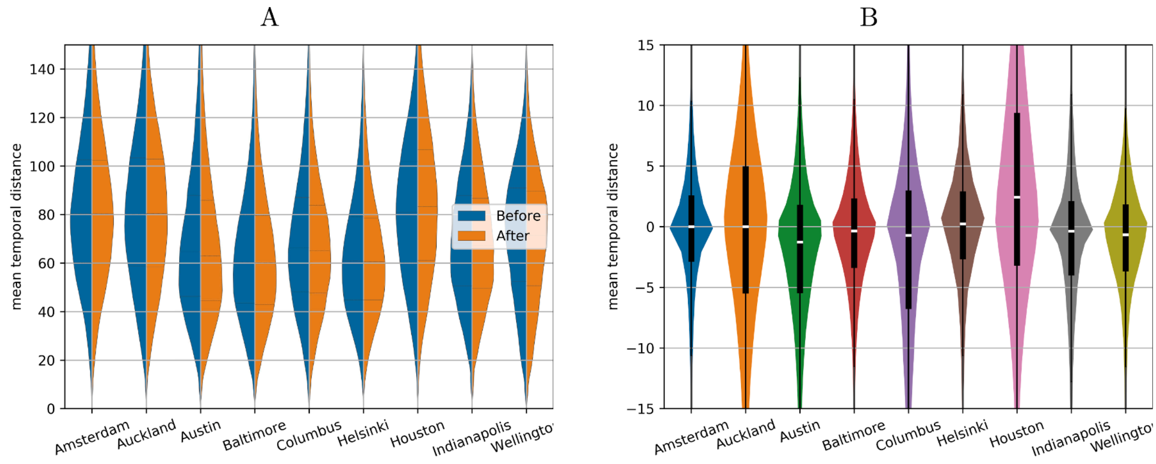

Fig. 5. The distribution of mean travel times before and after implemented redesigns (panel A) and the distribution of changes in mean travel times (panel B).

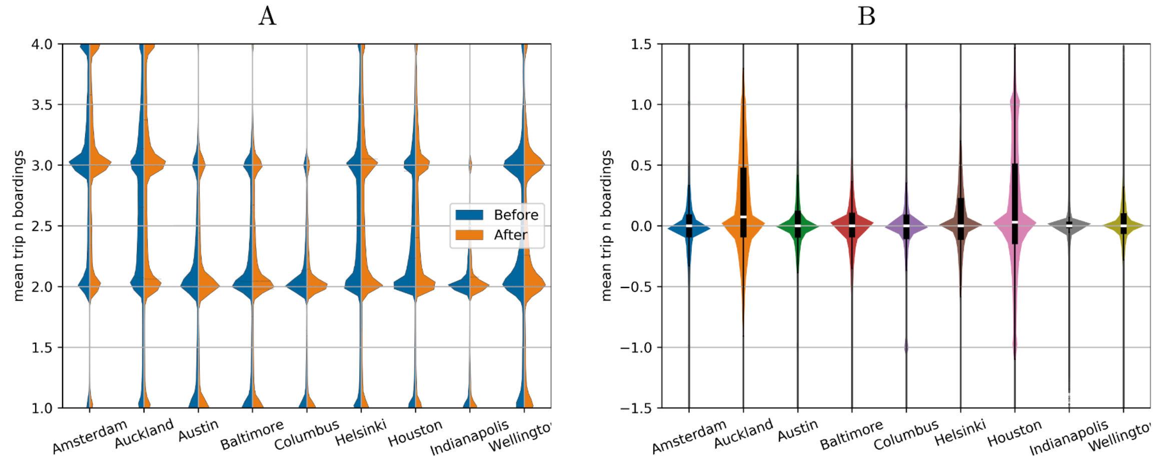

Fig. 6. The distribution of mean number of transfers before and after implemented redesigns (panel A) and the distribution of changes in mean number of transfers (panel B).

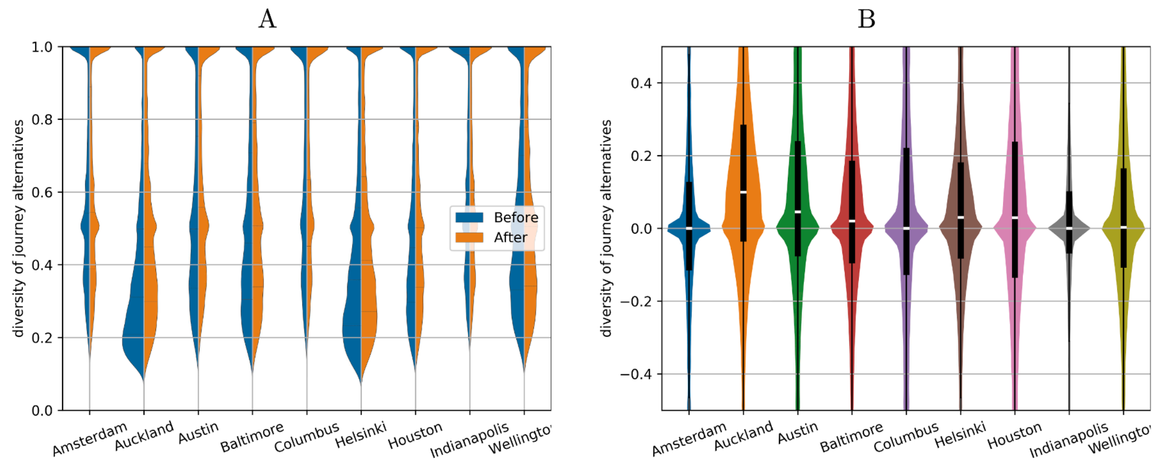

Fig. 7. The distribution of diversity of journey alternatives before and after implemented redesigns (panel A) and the distribution of changes in time-weighted diversity (panel B).

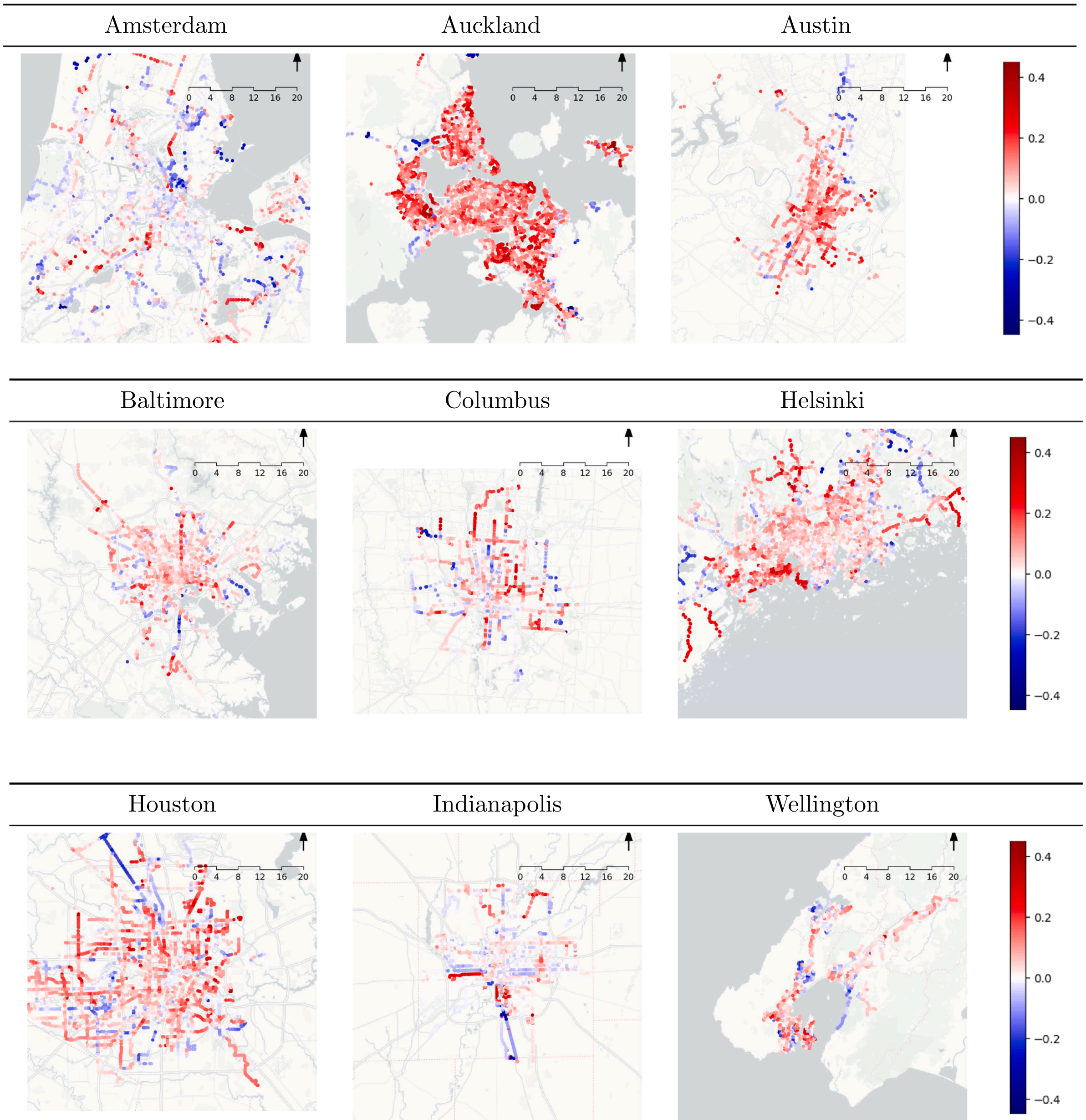

Fig. 8. Spatial distribution of the average change of diversity of journey alternatives. Positive values and red map color indicate a more uniform set of journey alternatives, suggesting improved navigability. Background map (c) OpenStreetMap contributors, (c) Carto. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

between contextual factors (e.g., PTN governance) and the resulting PTN redesigns.

6.2. Policy and planning implications

Adding further empirical depth to previous arguments from PT planning guidance documents (Nielsen et al., 2005; McLeod et al., 2017), this research draws a handful of lessons for planning and policy processes. Overall, although the effects of PTN redesigns from a navigability standpoint seems encouraging, it is important to consider the underlying trade-offs and dilemmas faced by those planning PTN. Underlining that PTN design belongs to the "NP-hard" class of problems, the choice set includes a multitude of design elements (Magnanti and Wong, 1984; Guihaire and Hao, 2008; Farahani et al., 2013). These elements span from choice of PT modes and integration with other modes to spatial elements such as right-of-way and route alignments to the schedule structure including headways and service span. Considering the limited resources assigned for PTN operation, and fluctuations in travel demand during the day, planners do not only decide upon dividing the resources between routes but also between different times of the day. Besides the range of interdependent design elements, PTN redesign processes also include a wide range of often-conflicting criteria, due to the dynamic involvement of a multitude of planning actors (Eräranta and Mladenović, 2020). Thus, PTN redesign process often revolves around making choices among a set of difficult-to-distinguish alternatives, which all result in unequal effects for different users and different criteria.

The key argument of this research is that PTN redesign processes should add navigability to the list of inherent trade-offs to be assessed ex-ante. This addition of navigability certainly does not directly remove labour needed during a PTN redesign process, as it requires trading off with conventional measures, such as travel time and transfers. In addition, navigability by itself introduces a multitude of, sometimes contradictory, meanings for PTN planning. In particular, navigability impacts range from very specific, concerning a particular origin–destination pair at a set time, to the daily and long-term structure of the PTN as a whole. The former is of concern for specific mobility patterns with specific destinations and times of day, while a more system-level knowledge of the PTN affects the confidence and ability to travel spontaneously to unfamiliar destinations or at unusual times of the day. Moreover, there is the long-term comprehension of the network which is disrupted or encouraged by redesign (Dziekan, 2008). Consequently, the ways navigability is measured needs to reflect this multidimensionality, necessitating the use of a framework with multiple complementing measures taking into account both spatial and temporal dimensions. For instance, schedule changes made to provide longer service hours are likely to make the provided service easier to memorize, as the daily schedule structure is more homogeneous. However, these changes will not be evident when analysing a snapshot of the journey alternatives at a specific time of day.

A good example of another trade-off during PTN redesign is that of direct routes versus a system of more frequent trunk routes. The clear difference from the user perspective is that the latter has the caveat of requiring more transfers to reach certain destinations. On the contrary, direct routes are more straightforward for navigability as long as a few routes can cater to the user's needs. However, the challenge with a structure providing direct connections is that the service will be less frequent (e.g., due to underlying resource constraints) and the whole PTN will have a large number of routes and route variants. Thus, PTNs with direct routes are mainly suitable when most destinations are concentrated in one location, such as a central business district. On the contrary, the user is more likely to familiarize herself with a more diverse set of destinations within a PTN based on trunk-routes, as there are fewer routes to comprehend. However, considering the increase in the reliance on transfers, there will be an increase both in the travel impedance in general but also in the cognitive load imposed by the journey legs and potential wayfinding at the transfer location (Timpf and Heye, 2002). The question of directness versus frequency also has implications for network vulnerability (Yang et al., 2017; Frappier et al., 2018). When considering the diversity of journey alternatives, having multiple redundant alternatives adds to system robustness while the presence of direct alternatives removes transfer risk. However, in case of transfers being unavoidable, a frequent system reduces transfer times and knock-on delays in case of missed transfers. Furthermore, trunk-systems tend to be sparser, requiring longer walking distances and more wayfinding at both the origin and destination trip ends. Thus, the two principal strategies of adaptation, i.e., changing the number routes and adapting the frequency of a fixed network, will have very different navigability implications for the reasons previously stated. For a more thorough assessment, it is thus imperative to measure navigability from multiple angles and at different times of the day, highlighting both the network structure and the user perspectives.

As stated earlier, the complexity of PTN redesigns and PT planning in general is not limited to navigability as defined in this research. We acknowledge that there are many more constraints in practice, such as topographical and budgetary limitations, and many more objectives, such as robustness or minimizing emissions, especially important having in mind direct effects on the ongoing climate crisis. In addition, PTN redesign also relates to other PT policy and governance aspects, such as fare structure, responsibilities for service implementation, and PT funding scheme. Thus, providing more specific policy implications for any of the nine case cities, or any other city around the world, would also mean significant neglect of the policy context that we know shapes PT planning (Roschlau, 2008; van de Velde, 2008; Walters, 2008; Weckström and Mladenović, 2020). Moreover, it would also mean neglecting the diverse socio-cultural contexts around the world, which relate to various effects from PTN redesign. For example, in some places in the Global South, large cities have a significant population with lower income levels, relying solely on PT for daily traveling to job opportunities, which often involves traveling long distances. The fact that these cities have a significant population that is both money and time poor could mandate different emphasis on assessment, for instance, related to fare structure.

Given the above challenges, the question remains - how should we conduct PTN redesign processes to find an acceptable balance between the variously identified trade-offs while avoiding effects perceived as unfair by some users? Fortunately, we already have lessons from in-depth case studies highlighting the procedural aspects of PTN redesign in cities around the world (Currie and Tivendale, 2010; Kash and Hidalgo, 2014; Muñoz et al., 2009; Muñoz et al., 2014). These and other case studies highlight the timing of assessment tasks and the role of public participation within planning processes. The reality is that PT planning still relies on the separation of tasks involving infrastructure and alignment planning, which are usually done first, and tasks involving the development of PT schedules. This in-built procedural path dependence means that adverse effects are usually assessed too late in the planning process, or even only after implementation of PTN redesign. As an undesired consequence, a redesign can lead to low user satisfaction overall, resulting in a modal shift away from PT, or a negative impact on well-being for those PT-dependent users.

7. Conclusion

This paper presents a comparative study of the impacts of redesigning PTNs in nine major cities in the Global North, using the concept of navigability. The redesigns included in this paper focused on varying aspects of the PTN, which requires attention when assessing the navigability impacts from a user and system-level perspective. Previously, navigability was a research topic that has been studied using a range of approaches and methods, including network science, wayfinding, and transport modelling. The purpose and perspectives of these approaches are different. Network science use navigability as a tool to describe the network on a general level, while wayfinding is a very human-centered, but data-hungry and, in existing research, mainly a place-specific approach. Furthermore, transport modelling focuses on predicting behavior, not describing the full complexity of available choices. Consequently, the way navigability is currently taken into account in research and practice is rather simple, as only the number of transfers and the number of route alternatives in route choice generation act as pseudo indicators. The objective of this paper was to fill the gap between the previous research strands by combining the network dimension with an approach closer to the way PT users are experiencing the PTN complexity. The proposed analysis framework focuses on both the aggregate point of view of the PT system as a whole and on impacts from the users' perspective, where journey-level navigability is understood through the diversity of travel alternatives that users experience as the result of PTN redesign. A range of new navigability measures was proposed, enabling a multidimensional understanding of navigability challenges. Results indicate that the implemented changes brought a mix of effects depending on the city, location within the city, and time of day. In general, all nine cities aimed at achieving a more hierarchical PTN, including strengthening the trunk-feeder system and changes in frequencies, as well as some additions of new PT modes. The analysis concludes that PTN redesigns studies brought important improvements for the navigability of PT users. Therefore, the change in the navigability from the user perspective must be considered and evaluated in future PTN redesign projects, including trade-offs with other decision criteria, for achieving equitable outcomes.

The development presented in this paper opens up pathways for several future research directions of useful PT planning support systems, which are capable to support decisions around trade-offs inherent to PTN planning processes in practice. First, there is a need for furthering connections to route choice and travel experience modelling efforts that are bringing about a further understanding of PT users. In particular, there is a need to increase the understanding of how navigability impacts travel behavior in conjunction with other, more widely researched, travel impedance factors such as travel time, transfers, and fare structure. In addition, of particular interest is the relationship between the navigability at the network level and wayfinding at stops. Such research should also focus on drawing from user segmentation studies or developing own user types, including their travel behaviour criteria as part of the modelling framework. Second, there is a need for furthering the understanding of the long-term changes in PTNs in relation to navigability, but also mode change in general. While transforming into a more navigable PTN may make it easier to attract new passengers, changes in the PTN always require the existing users to relearn the system. Especially challenging are large-scale redesigns that often introduce changes in many areas ranging from route numbering to modes, often over a very short period. This raises the question of whether PTN redesigns in all cases are worthwhile considering the aims of the undertaking. Thus, further research should focus on comparing incremental with more abrupt transition processes in practice. Finally, we need further in-depth case studies accounting for the depth and diversity of local contexts. Such case studies can relate to a multitude of local factors, such as topography, city structure, PT demand, planning cultures, and political economy. With the increase in case studies, it may be possible to draw further lessons regarding various trade-offs made in PTN planning practice across diverse planning cultures worldwide.

CRediT authorship contribution statement

Christoffer Weckström: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Miloš N. Mladenović:** Conceptualization, Resources, Writing - original draft, Writing - review & editing, Supervision, Project administration, Funding acquisition. **Rainer Kujala:** Conceptualization, Methodology, Software, Data curation, Writing - review & editing, Visualization. **Jari Saramäki:** Resources, Writing - review & editing, Supervision, Project administration, Funding acquisition.

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