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Modelling travel time in urban networks: comparable measures for private car and public transport

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ABSTRACT

Analysing the accessibility disparity between different travel modes is recognised as an efficient way to assess the environmental and social sustainability of transport and land use arrangements. Travel times by different travel modes form an essential part of such an analysis. This paper aims to assess the comparability of different methods for calculating travel time by different travel modes. First, we briefly review the methods used in previous studies and identify different typical approaches, which we then compare. We use three computational models respectively for car and public transport (PT), implemented in our case study area, the capital region of Finland. In the car models, (1) the simple model ignores congestion and parking in travel time calculation; (2) the intermediate car model accounts for congestion but ignores parking; and (3) the more advanced car model takes into account all parts of the journey, including congestion and parking. For PT, (1) the simple model accounts for transit routes but ignores schedules; (2) the intermediate model incorporates schedule data in a simplistic way; and (3) the more advanced model adopts a door-to-door approach where true schedules (incl. congestion) and realistic route combinations are accounted for. Our results show that absolute differences in car and PT travel times are notable in the Greater Helsinki area, no matter which models are used for comparison. Modal travel time disparity appears smallest in the city centre area. We conclude that using conceptually corresponding models for car and PT travel time calculations is the key to achieving a reliable analysis of modal accessibility disparity. A door-to-door approach in travel time calculations (adopted in the most advanced models) also makes the results truly comparable in absolute terms. Finally, the more advanced the applied methods are, the more data hungry the analysis is. Here, recent developments in open data policies among urban transport data producers become very helpful.

1. Introduction

Accessibility analysis is considered an appropriate way to assess interactions between transportation and land use (Bertolini et al., 2005; Silva and Pinho, 2010). Different distance measures typically form an integral part of accessibility indicators and travel time is often considered to be an intuitive measure that corresponds well to people's perceptions of friction of distance (Frank et al., 2008; Mavoa et al., 2012). Traditionally travel time has been calculated using the privately owned car as the subject but concern over the environmental and social sustainability of land use and transportation solutions has in recent years highlighted the need to incorporate different modes of transport in accessibility analyses.

Comparing the accessibility provided by different travel modes and identifying modal accessibility disparities can provide a useful approach in assessing the degree of auto-orientation in the urban structure (Kawabata, 2009). Given the challenges of sprawl in many urban regions (EEA, 2006; Hepinstall-Cymerman et al., 2013) and the related development of car dependency (Filion, 2000), this is particularly topical. Modal comparisons are also interesting from the social equity point of view: people who are not driving for financial, physical or lifestyle-related reasons may face considerable difficulties in accessing services and opportunities (Kawabata, 2003; Martin et al., 2002).

The few existing studies on modal accessibility disparity show that in the majority of US and European urban regions private car provides much better levels of access than public transport (Hess, 2005; Kawabata, 2003; Kawabata and Shen, 2007; Levinson, 1998; Shen, 2001; Silva and Pinho, 2010). Hong Kong seems to be the only exception in that accessibility between traffic zones was actually found to be much better by public transport than by car (Kwok and Yeh, 2004). The comparability of these studies remains

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questionable though, given that the spatial scale of analysis varies between studies and the accessibility analyses are based on different types of methods and data. In some cases, travel times are provided by the authorities (and it remains unclear how these were produced) whereas in other cases travel time calculations form an integral part of the analysis. Even within each of the above mentioned papers the modal comparison might prove problematic because methods used to produce accessibility values for the different modes are either not reported in detail or are incompatible (see also Benenson et al., 2011). Indeed, several simplifying assumptions are typically made when modelling either car or public transport travel times. Yet, making solid decisions on data, parameters and assumptions underlying travel time analyses is of fundamental importance for the reliability of the results.

In this paper, we evaluate the comparability of different methods for calculating travel times by car and by public transportation. We identify three travel time calculation models for both these travel modes based on approaches presented in the literature. We implement these models for Greater Helsinki and to a varying degree include the typical "simplifying assumptions" that are commonly used in travel time analysis. The different models are then used for measuring travel times from all the inhabited grid squares of Greater Helsinki ($n \approx 6900$) to relatively equally distributed real-life points of interest (the 59 public libraries of the region). We compare the results of different models, assessing their suitability for studies that focus on modal accessibility disparity. A simple travel time ratio between the analysed travel modes is used to measure the modal accessibility disparity. We aim at understanding how the different analysis methods affect travel times and trip distances on the one hand, and the range and spatial distribution of the modal travel time ratio on the other.

2. Different approaches to measuring travel time

2.1. Travel time by private car

Many countries maintain digital road databases with road centreline geometries and extensive attribute information (speed limits, one-way streets, etc.). Network analysis tools in standard GIS software provide an easy way to conduct car drive-time analysis based on such data: road segment length divided by the respective speed limit provides an estimate of "free-flow" drive-through time for the segment, and the optimal route between given origins and destinations is calculated using a shortest path algorithm. The problem with such an approach is that it ignores congestion, time spent to find a parking space and necessary walking times to and from the parking space – all of which may substantially alter travel times in urban settings (Christie and Fone, 2003; Martin et al., 2008; Yiannakoulias et al., 2013).

There are studies that in some way incorporate congestion or other local conditions when determining travel speeds (e.g. Hess, 2005; Lovett et al., 2002). Often the ways in which this is realised are not reported in detail – rather the authors state that they have used "realistic average travel speeds" but the grounds for these estimates are not described. Christie and Fone (2003) tested how analysis results on hospital access in Wales are affected if travel speeds underlying travel time calculations are altered and concluded that the measurements are highly sensitive to the assumed travel speeds. Yiannakoulias et al. (2013) tested the effect of including congestion values and turn penalties in travel time calculations in Edmonton and suggested that absolute travel times are drastically changed by including these factors while gravity-based relative accessibility measures are more robust to travel time metrics. The fact that absolute travel times are sensitive to changes in impedance values is hardly surprising as such, but the above examples provide a good reminder of how important it is to try to find the most appropriate impedance values for travel time analysis.

2.2. Travel time by public transport

Unlike car and other personal modes of transport, public transport is bound to predefined routes and schedules that depend on the time of day and the day of the week and are subject to frequent alteration. Typical shortcomings in public transport travel time calculations are simplifying assumptions related to travel speeds along the route and transfer times between different lines (Lei and Church, 2010). Given the lack of detailed schedule information, average travel speeds are typically assigned to the whole route, ignoring differences between different parts of the route (Liu and Zhu, 2004; Moniruzzaman and Páez, 2012; O'Sullivan et al., 2000; Peipins et al., 2011). Similarly, transfer waiting times are either ignored altogether or assumed to be constant in all transfers, for example one half of the headway time (time interval between vehicle departures) (Hess, 2005; Mavoa et al., 2012; O'Sullivan et al., 2000; Peipins et al., 2011; Tribby and Zandbergen, 2012). Furthermore, few studies in reality incorporate scheduled arrival or departure times in the analysis (however, see Lei and Church, 2010).

Standard GIS software rarely provide adequate tools and data structures for multi-modal routing that would be able to handle the temporal elements of public transport services (Martin et al., 2008). However, the recent development of data formats (such as the General Transit Feed Specification (GTFS)) has opened up new opportunities, and electronic journey-planning services based on such data are now also provided for transit users (cf. car route search sites). Although the potential of these data formats and web-based services from the research point of view was anticipated over a decade ago (Martin et al., 2002), their use for research purposes has only recently begun (e.g. Eluru et al., 2012; Jäppinen et al., 2013; Lei and Church, 2010).

2.3. A door-to-door approach

Some studies take into account every stage of a journey between its origin and destination when analysing travel times and distances (Benenson et al., 2011; Lei and Church, 2010; Liu and Zhu, 2004). In this paper, we define this "door-to-door approach" as follows (Fig. 1): By car, a door-to-door journey includes (1) walking from the point of origin to the place where the car is parked; (2) driving from the parking space to near the destination; (3) looking for a parking space near the destination, and, finally, (4) walking from the parking space to the destination itself (cf. Benenson et al. (2011) whose approach is otherwise similar but ignores the time needed for finding a parking space (step 3 in our approach)). By public transport, the journey may be slightly more complicated. The basic parts include (1) walking from the point of origin to the appropriate stop ("access time"); (2) waiting for the transport vehicle to arrive and to depart; (3) sitting in the vehicle between the initial and final stops; and (4) walking from the last stop to the final destination ("egress time"). In addition, many public transport journeys include transfers from one route to another, which possibly imply walking from one stop to another and waiting for the next vehicle to depart (see Benenson et al. (2011) and Lei and Church (2010) for similar approaches).

3. Greater Helsinki as the case study area

The empirical part of this paper takes place in Greater Helsinki, the capital region of Finland (Fig. 2). Greater Helsinki comprises

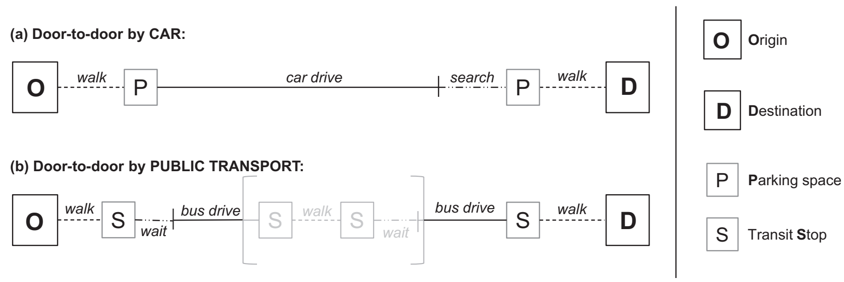


Fig. 1. Examples of the door-to-door approach in (a) car journeys and (b) PT journeys.

four municipalities and has approximately one million inhabitants. The highest population densities are found in the city centre of Helsinki and along suburban railway lines.

In 2008, 39% of daily trips in the Greater Helsinki area were done by car whereas the share of public transport trips was 26% (HRT, 2010). The road network of the region relies on a few large ring roads (west-east) and several radial roads originating from the city centre of Helsinki (Fig. 2). Congestion during the rush hour is concentrated on the area inside the inner ring road and on the radial roads leading to the city centre, and congestion charges are a hot topic in contemporary urban politics (Välipirtti et al., 2011). Parking is challenging particularly in the city centre (Kurri and Laakso, 2002).

The public transport system of Greater Helsinki relies on an extensive bus network and a few railway lines, complemented by trams and a metro within the municipality of Helsinki. In total, there are roughly 600 transit lines in the region (excluding service lines and night buses). Overall, the current structure of the public transport network is highly city centre oriented and crosstown connections are one of the key development areas of public transport planning.

4. Materials and methods

4.1. Study design

In order to test the comparability of travel time analyses by different travel modes, we performed a set of routing analyses for both car and public transport (Fig. 3). As route origins we used centroids of inhabited grid cells in Greater Helsinki. The alignment of the 250 m $\times$ 250 m cells corresponded to the Grid Database of Statistics Finland (2012) and the inhabited grid cells were identified based on building-level population data in SeutuCD 2009 (Table 1). The routes' destinations were 59 public libraries, which are one of the most actively used public services in Finland (Vakkari and Serola, 2012). Here, the type of destinations was fairly unimportant, since the primary aim of this paper is to perform methodological comparisons – thus, rather than the type of facility, their spatial distribution was the main criterion for their selection. Public libraries are quite evenly distributed in the study area (Fig. 2) and thus provide a relatively representative sample of different areas around Greater Helsinki.

We calculated travel times and network distances between all origins and all destinations, using three different models for each travel mode, here named as *simple*, *intermediate* and *advanced* model. We also computed Euclidean distances between all origins and destination, in order to show how much more complicated real-life travel routes are in our study area in comparison to Euclidean distances which in many cases are used as accessibility surrogates (e.g. Boscoe et al., 2012; Phibbs and Luft, 1995). The chosen grid cell resolution naturally affects the distance calculations (larger grid cells leading to increased inaccuracy in results) and we deemed the 250-m cell to be sufficiently detailed for our purposes. With this grid cell size, the time needed for computations was reasonable, and yet, the positional error resulting from aggregation of the building level data was rather minor and did not have consid-

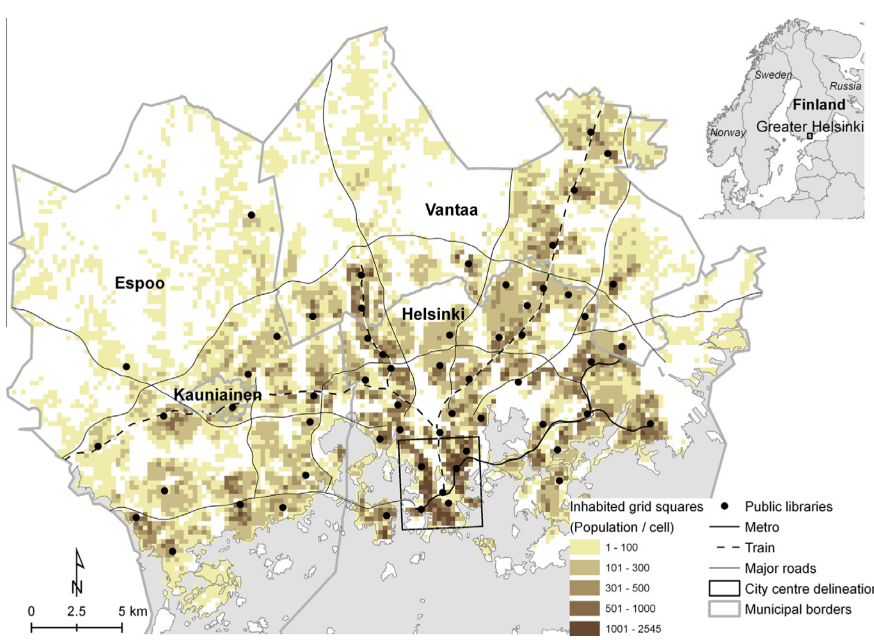


Fig. 2. Study area. Background map © The City Survey Division of Helsinki, municipalities of Greater Helsinki, HSY, 01.01.2012.

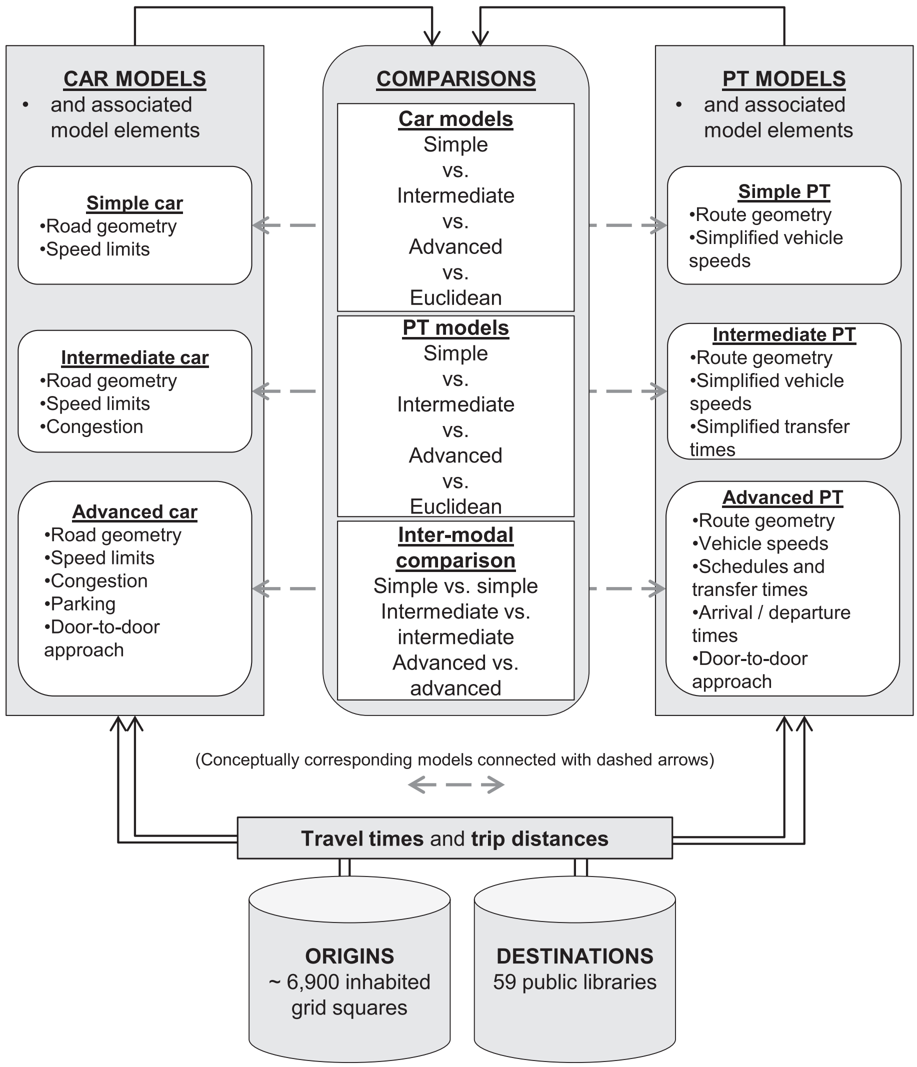


Fig. 3. Workflow of the study.

erable effect on the accuracy of the distance (and time) calculations.

We compared travel times and distances between the different models by calculating their mutual ratios and correlations: For example, travel times produced by the simple and intermediate car models (see Section 4.2) were compared for each origin–destination pair by calculating the ratio between the two. These ratios were then averaged and the Pearson correlation coefficient was calculated to reveal how well the values produced by the different models correlated with each other. Similar assessments were done between all models, both for travel times and trip distances (including Euclidean distances).

Finally, travel time ratios between the travel modes (PT travel times divided by car travel times) were visualised as maps.

4.2. Car models

The *simple car model* used the national road and street database Digiroad as the routing network dataset (Table 1). Each road segment had a speed limit attributed to it, and these speed limits together with the segment lengths determined the drive-through time of each segment. Digiroad was also used in the *intermediate car model* but the speed limit-based impedances were adjusted to fit the real-life driving times in the case study area. This was done by assigning cross roads a deceleration value which was different for each road class (cf. Määttä-Juntunen et al., 2011; Thériault et al., 1999; Yiannakoulias et al., 2013). The deceleration values were derived from floating car measurements (for more on the floating car method, see Li et al., 2011) where real travel speeds along different roads of the study area were measured during normal weekdays in spring and autumn 2009, at different times of the day (data sources in Table 1). Based on a regression analysis, the effect of functional road classes and crossroads on travel speeds was formulated to deceleration values which in this case corresponded to average deceleration during a day (Jaakkola et al., in press). Crossroads on road classes 1 and 2 (regional main roads/streets) got a daily average deceleration value of 11.31 s; crossroads on road class 3 (local main streets/regional roads) got 9.44 s; and crossroads on road classes 4–6 (collector streets/connecting roads, feeder streets and private roads) got 9.36 s. Drive times were calculated using the Network Analyst extension in ArcGIS 10 where the route optimisation was based on the fastest (not necessarily the shortest) route between all origins and destinations.

The *advanced car model* was built on the intermediate model but it also included the time spent walking from the point of origin to the parking space at the start of the journey, the time spent searching for a parking space at the destination, and, finally, the time spent walking from the parking space to the destination – in other words, the advanced model used the previously presented

Table 1
Data sources.

Dataset	Reference[a]	Description	Phase of analysis
Driving speeds	Helsinki Region Transport/Helsinki City Planning Office	Floating car measurements of real-life driving speeds along main roads	Preparation of intermediate and advanced car routing data
Parking studies	Kurri and Laakso (2002)/Kalenoja and Häyrynen (2003)	Empirical studies on parking conditions in the Greater Helsinki area and other city areas in Finland	Preparation of advanced car routing data
Digiroad	Finnish Transport Agency (2011)	National road and street database	Simple car model
Modified Digiroad	Jaakkola et al. (in press)	Digiroad data modified to correspond to local driving conditions	Intermediate and advanced car models
Public transport routes	SeutuCD (2009)	Geometry of the public transport network in the Greater Helsinki area	Simple and Intermediate PT model
Average PT route times	Helsinki Region Transport (2012)	Average route times for each public transport route	Simple and intermediate PT model
Average PT headway times	Helsinki Region Transport (2012)	Average headway times for each public transport mode	Intermediate PT model
Journey Planner API	Helsinki Region Transport (2011)	Application Programming Interface to Helsinki region public transportation timetable and route database	Advanced PT model
Population statistics	SeutuCD (2009)	Building-level statistics on population in the study area, aggregated in 250 × 250 m cells	OD-matrix (origins)
Libraries	Helmet libraries	Location of public libraries in the Greater Helsinki area	OD-matrix (destinations)

SeutuCD (2009). Produced by Helsinki Region Environmental Services Authority.
Helsinki Region Transport (2012). http://www.hsl.fi/EN/timetablesandroutes/Pages/default.aspx.
Helsinki Region Transport (2011). http://developer.reittiopas.fi/pages/en/home.php.
[a] Finnish Transport Agency (2011). http://www.digiroad.fi/en_GB/.

door-to-door approach. We used empirical studies on parking conditions in the Greater Helsinki area and other city areas in Finland to determine the average walking distances between the point of origin and the parking space and between the parking space and the destination: in the city centre area the average distance was defined as 180 m and outside the city centre as 135 m (Kurri and Laakso, 2002). These were average distances for all types of parking spaces, and determined based on a survey that was conducted in May 2000 (most of the answers were gathered on normal weekdays, but part of the answers during a Saturday) (Kurri and Laakso, 2002). We applied these distances both at the beginning of the journey (distance from the origin to the parking space) and at the end of the journey (distance from the parking space to the destination). Distances were then transferred as times, using a walking speed of 70 m/min which is a default value for walking speed in the Journey Planner route search application (see Section 4.3) (HRT, 2011). The time spent in searching for a parking space at the destination was defined as 0.73 min, which is an average value for on-street parking on a normal weekday (Kalenoja and Häyrynen, 2003).

4.3. Public transport models

The *simple PT model* was based on a multimodal network dataset created in ArcGIS 10. In the dataset, public transport routes and their associated stops were grouped by travel mode, and each mode formed its own connectivity group in the network dataset. These groups were connected to each other through a pedestrian network represented by the Digiroad data (which contains pedestrian roads in addition to roads for motorised transport). The time needed to cover each pedestrian segment was calculated using a walking speed of 70 m/min. Connections between the PT network and the pedestrian network were modelled by straight lines between each PT stop and the closest edge element along the pedestrian network (boarding/exit lines). Travel times by each mode were calculated based on an average speed of the respective travel mode (derived from route lengths and approximate route drive-through times on a normal weekday during the winter schedules) (Tables 1 and 2). Walking from the origin point to the closest PT stop and walking from the last PT stop to the final destination were ignored, and the origin and destination locations were snapped directly to the closest PT stop. The simple model also ignored transfer times.

Table 2
Mode-specific average speeds and transfer times used in the simple and intermediate PT models.

PT travel mode	Average speed (km/h)	Transfer time (average headway time (min)/2)
Bus	26.3	12.3
Tram	13.3	4.7
Metro	39.9	4.5
Train	54.1	14.9

The *intermediate PT model* used the same network dataset structure and the same mode-specific average speeds as the simple model. It differed in that it accounted for transfer times: half a headway time was added to the in-vehicle travel time when the first PT vehicle was entered and if transfers occurred from one travel mode to another. Headway times were mode-specific and based on average scheduled headway times around the morning rush hour (8 am) and outside rush hour (12 pm) on a regular weekday during the winter schedules (Table 2). In the network dataset, transfer times were assigned to the boarding lines.

The *advanced PT model* used the Journey Planner API (HRT, 2011), which contains data on up-to-date public transport routes and schedules in the study area. The PT schedules are planned to take into account congestion-related delays in route drive-through times. The databases of the API were queried using tools developed in-house (see Jäppinen et al., 2013; the source codes of the tools are available in Github https://github.com/matti/reittihaku). In order to account for the daily variation in schedules, we performed four route searches between each origin and destination, two during the rush hours and two outside the rush hours. Each route search resulted in three alternative route suggestions and the final travel times and distances are the average values of these 12 routes (4 timeslots × 3 route suggestions). The door-to-door approach is inherently included in the Journey Planner routes, which include the walk from the origin to the first PT stop, all the necessary PT

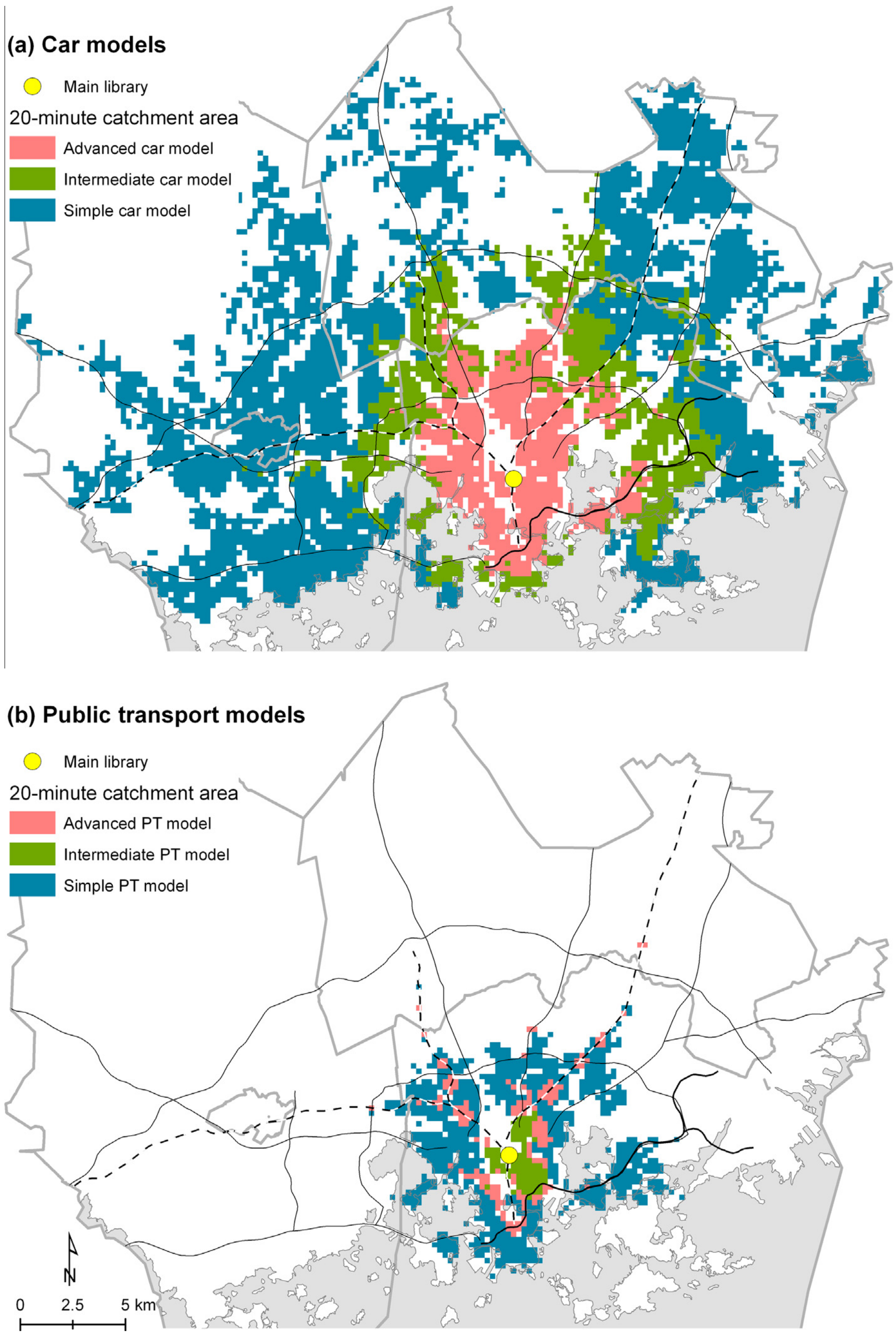


Fig. 4. 20-min catchment areas around the main library produced by (a) car models and (b) PT models. Background map © The City Survey Division of Helsinki, municipalities of Greater Helsinki, HSY, 01.01.2012.

routes and transfers, and the walk from the last PT stop to the final destination. All route searches were performed using the winter schedules and a normal weekday. Route search settings were the default settings provided by the Journey Planner (e.g., walking speed 70 m/min) (for more detailed description of default values, see HRT, 2011).

5. Results

5.1. Model comparisons within each mode

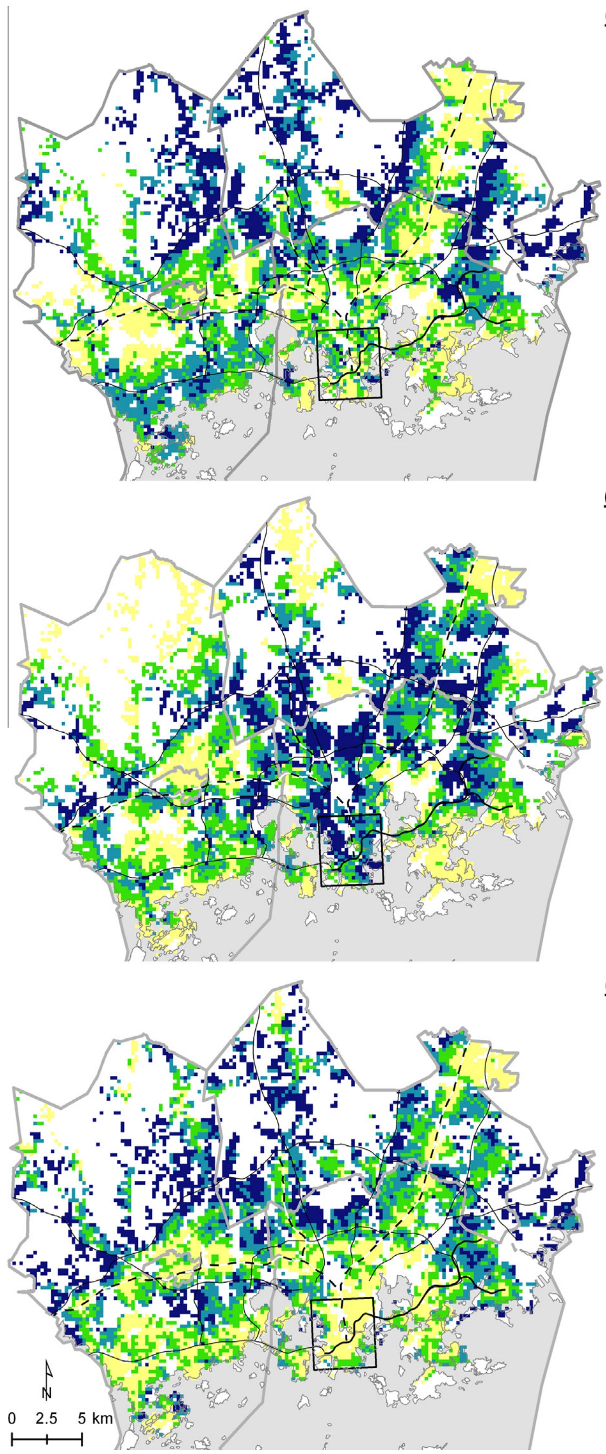
The differences between the models are illustrated in Fig. 4, where a 20-min catchment area around a selected destination (the main library) is drawn using all the models (4a: car models; 4b: PT models). In the simple car model, a majority of inhabited grid cells (5914) is reached within a 20-min drive. Within the same time, the intermediate car model reaches 1982 cells and the advanced car model reaches 861 cells. The 20-min catchment areas in the PT models are much smaller than in the car models but there are notable differences between the PT models: the simple model reaches 985 cells, the intermediate model 85 cells and the advanced, 234 cells.

When looking at trips from all origins to all destinations, correlations between all the models are high and statistically significant (>0.82**) (Table 3). In the car models, travel times in the advanced model are on average over twice as long as in the simple model. In

Table 3
Pair-wise comparison of different models: Average ratios between median travel times and trip distances in the different models (Pearson correlations in parentheses).

	Simple car		Intermediate car		Advanced car		Simple PT		Intermediate PT		Advanced PT		Euclidean distance
	TT	TD	TT	TD	TT	TD	TT	TD	TT	TD	TT	TD	TD
Simple car													
TT	1 (1.00**)												
TD	– (.972**)	1 (1.00**)											
Intermediate car													
TT	1.76 (.977**)	– (.938**)	1 (1.00**)										
TD	– (.973**)	1.05 (.980**)	– (.956**)	1 (1.00**)									
Advanced car													
TT	2.20 (.976**)	– (.934**)	1.24 (.998**)	– (.953**)	1 (1.00**)								
TD	– (.973**)	1.08 (.980**)	– (.956**)	1.03 (1.00**)	– (.954**)	1 (1.00**)							
Simple PT													
TT	2.18 (.928**)	– (.924**)	1.25 (.903**)	– (.914**)	1.02 (.903**)	– (.914**)	1 (1.00**)						
TD	– (.933**)	1.06 (.961**)	– (.901**)	1.02 (.942**)	– (.897**)	0.99 (.942**)	– (.928**)	1 (1.00**)					
Intermediate PT													
TT	3.41 (.954**)	– (.969**)	1.94 (.928**)	– (.959**)	1.57 (.925**)	– (.959**)	1.61 (.953**)	– (.967**)	1 (1.00**)				
TD	– (.955**)	1.00 (.977**)	– (.927**)	0.96 (.962**)	– (.923**)	0.94 (.962**)	– (.925**)	0.95 (.972**)	– (.981**)	1 (1.00**)			
Advanced PT													
TT	3.53 (.869**)	– (.855**)	2.01 (.843**)	– (.847**)	1.62 (.847**)	– (.847**)	1.67 (.888**)	– (.861**)	1.04 (.878**)	– (.861**)	1 (1.00**)		
TD	– (.938**)	1.19 (.955**)	– (.912**)	1.14 (.939**)	– (.910**)	1.11 (.939**)	– (.946**)	1.14 (.960**)	– (.962**)	1.20 (.962**)	– (.919**)	1 (1.00**)	
Euclidean distance													
TD	– (.948**)	0.72 (.974**)	– (.916**)	0.69 (.963**)	– (.913**)	0.68 (.963**)	– (.907**)	0.69 (.955**)	– (.962**)	0.73 (.973**)	– (.830**)	0.62 (.937**)	1 (1.00**)

TT = Travel time.
TD = Travel distance.
** Correlation is significant at the 0.01 level (2-tailed).



(a) Simple models

Model	Variable	Mean	Std. Deviation
Simple car	Travel time (min)	16.6	6.9
	Trip distance (m)	18459.1	8991.9
Simple PT	Travel time (min)	36.1	15.5
	Trip distance (m)	19691.8	10166.3

Travel time ratio (simple PT / simple car)

1.24 - 2.01; 2.02 - 2.15; 2.16 - 2.33; 2.34 - 3.56

Highlights
- small differences along railway lines
- ratio within city centre: 2.08
- ratio outside city centre: 2.18

(b) Intermediate models

Model	Variable	Mean	Std. Deviation
Intermediate car	Travel time (min)	28.9	11.5
	Trip distance (m)	19358.5	9359.1
Intermediate PT	Travel time (min)	53.8	18.9
	Trip distance (m)	18303.1	8861.7

Travel time ratio (intermediate PT / intermediate car)

1.39 - 1.81; 1.82 - 1.94; 1.95 - 2.07; 2.08 - 4.61

Highlights
- large differences along ringroads
- large differences within downtown
- ratio within city centre: 2.05
- ratio outside city centre: 1.94

(c) Advanced models

Model	Variable	Mean	Std. Deviation
Advanced car	Travel time (min)	34.4	11.6
	Trip distance (m)	19697.8	9365.4
Advanced PT	Travel time (min)	55.7	20.8
	Trip distance (m)	21801.8	10474.6

Travel time ratio (advanced PT / advanced car)

1.00 - 1.47; 1.48 - 1.60; 1.61 - 1.74; 1.75 - 3.06

Highlights
- small differences within downtown
- small differences along railway lines
- large differences along the outer ringroad
- ratio within city centre: 1.39
- ratio outside city centre: 1.63

Fig. 5. Spatial distribution of travel time ratios in the (a) simple car and simple PT models; (b) intermediate models and (c) advanced models. Note that class intervals vary between maps. Background map © The City Survey Division of Helsinki, municipalities of Greater Helsinki, HSY, 01.01.2012.

comparison to the intermediate model, the advanced model travel times are less than 25% longer. Differences in trip distances are, at the most, 8% (advanced vs. simple car model).

In the PT models, travel times in the advanced model are nearly 70% longer than in the simple model. In comparison to the intermediate model, the advanced model travel times are 4% longer. Differences in trip distances are, at the most, 20% (advanced vs. intermediate PT model).

Euclidean distances are around 30% shorter than trip distances along the road network in all the models. The biggest difference found was between the advanced PT model and Euclidean distances: Euclidean distances account for up to 62% of trip distances in the advanced PT model.

5.2. Intermodal model comparisons

When travel modes are compared to each other, the largest differences in average travel times are found between the advanced PT model and the simple car model (PT travel times over 3.5 times as long as car times) (Table 3). When the supposedly conceptually

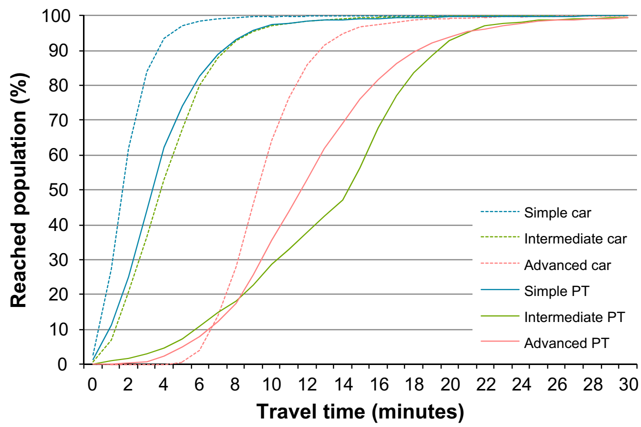


Fig. 6. Cumulative share of residents accessing the closest library within a certain travel time (car models: dashed lines/PT models: continuous lines).

corresponding models are compared (i.e. simple PT vs. simple car; advanced PT vs. advanced car), differences in average travel times are smallest between the advanced models (PT travel times on average are 1.62 times longer than car travel times). Among the simple models the average travel times are 2.18 times longer by PT and among intermediate models 1.94 longer by PT.

In trip distances the largest difference between the travel modes is found between the advanced PT model and the simple car model (1.19 times longer trips in the PT model). When the corresponding models are compared, the largest differences are found between the advanced models (on average 11% longer distances by PT).

The spatial distributions of modal travel time ratios are shown in Fig. 5((a) simple models; (b) intermediate models; (c) advanced models). The grid cell values reveal how much longer PT travel times are on average when looking at journeys to all destinations from the respective origin cell.

The smallest differences between the simple car and simple PT models are concentrated along the railway lines, meaning that the PT travel times from these areas to all destinations are at the maximum twice as long as car travel times. Southern parts of the city centre area are characterised by smaller differences but otherwise the city centre area is a mixture of high and low ratios, which means that in some parts of the city centre the average travel times by PT are up to 3.6 times longer than travel times by car. In the intermediate models, areas along the ring roads and in the inner city are characterised by high travel time ratios. Smaller values are found along the seashore in particular. In the advanced models, the city centre area has a considerable concentration of low ratios, meaning that in these models PT travel times are fairly competitive in relation to car travel times in the city centre. Other areas of low differences are found along the railway lines. The largest differences are concentrated along the edges of the study area, indicating that travelling by PT from these areas to the destinations is much slower than travelling by car.

Mean travel times are longer by public transport (36.1–55.7 min) than by car (16.6.–34.4 min), no matter which models are used for comparison (Fig. 5, embedded tables). Travel times in the intermediate models are longer than in the simple models, and, correspondingly, the advanced models produced longer travel times than the intermediate models. Mean trip distance, in turn, appears shorter in the intermediate PT model in comparison to its corresponding car model (18.3 km vs. 19.4 km, respectively). Furthermore, the mean distance in the intermediate PT model is shorter than in the simple PT model (18.3 km vs. 19.7 km, respectively). For comparison, the mean Euclidean distance is 13.5 km (standard deviation 7.0).

5.3. Travel time to the closest destination in the different models

Cumulative travel time curves show how much time it takes for the city's residents to get to their closest destination (Fig. 6). According to the simple car model, 95% of residents reach their closest destination in less than 5 min. The corresponding values in the intermediate and advanced car models are 9 min and 15 min, respectively. The simple PT model suggest that 95% of the population reach their closest destination in less than 9 min, while the corresponding value in both the intermediate and advanced PT models is 21 min.

Differences in trip distances among the models are much smaller and not shown as figures.

6. Discussion

6.1. The comparability of travel modes

Advanced GIS methods, the availability of open data sources and increasing processing capacity allow accessibility analyses to be relatively easily incorporated into scientific work and practical-level planning. With more modelling methods available, it is increasingly important to make sound methodological choices when conducting such analyses.

As we have demonstrated, it is essential to use conceptually corresponding models when comparing travel times between travel modes. Modal comparison based on conceptually different models (e.g. advanced PT vs. simple car) may result in unrealistically large differences; in our case study area, public transport might even appear to provide a much better level of accessibility than the private car (cf. simple PT vs. advanced car in Fig. 6), which is seldom realistic in the Greater Helsinki area. If travel times are to be analysed in absolute terms, the approach taken by the more advanced models presented in this paper is more reliable than the approaches in the simple and the intermediate models: In PT journeys, access and egress times and delays related to transfers may make up a considerable share of the total travel time. Furthermore, average speeds used by the simple and intermediate PT models ignore the effect of urban structural variables on speeds in different parts of the urban region. Similarly in the car models, congestion and time necessary for parking make the journeys last considerably longer and affect route choices too.

Travel time in urban surroundings is to a high degree dependent on the day of week and time of day (Lei and Church, 2010): thus, during weekdays and weekends and during rush hours and outside them the disparities between travel modes might appear somewhat different. At the very least, the model elements in the conceptually corresponding models should thus be based on the same day of week (as was the case in all our models). Indeed, the advanced models would allow a more detailed temporal analysis of accessibility disparity. The advanced PT model takes into account exact departure and arrival times and differences in route schedules that have been adjusted to traffic conditions at different times of day. Similarly, the deceleration values in the intermediate and advanced car model could be adjusted to correspond to rush/nonrush hours. In our case, data on parking conditions (walking distances and search times) were not detailed enough to allow for a temporal distinction but should such data be available, a temporal comparison of accessibility disparity could be carried out. This would definitively be an interesting theme for further examination.

One common simplification in public transport travel time modelling is the use of half headway time as a surrogate for transfer-related waiting time. Results from our study area show that the intermediate model (applying this assumption) clearly underestimates travellers' ability to optimise their journey: travel times on short journeys are considerably longer in the intermediate PT model than in the advanced PT model (cf. Fig. 6), and one logical explanation is that transfer times in the advanced model – based on true schedules – are likely to be shorter than the half headway time would suggest. Owing to this, modal comparisons based on the intermediate models suggest unrealistically large modal disparities on short journeys.

As our results show, travel times are much more sensitive to the underlying model than trip distances. Travel times within each travel mode get longer as the number of associated model elements (restricting rules) in the model grows. In terms of trip distances the effect of additional restricting rules may be different: PT trip distances were shorter in the intermediate than in the simple model, mainly because the simple model can "afford" to make longer trips within the same time, as transfers between modes have no cost associated with them.

6.2. Findings on accessibility disparity

In the Greater Helsinki area, absolute differences in travel times between travel modes are notable – no matter which models are used for comparison. When conceptually corresponding models are compared, the relative modal differences are quite similar in the simple and intermediate models but considerably smaller in the advanced models.

These results partly challenge some recent findings: Benenson et al. (2011) found in Tel Aviv that the observed accessibility gap between travel modes tends to grow if public transport analysis is done in more detail (using the door-to-door approach). Their public transport data takes into account walks at the start and end of the journey (though not in as much detail as in our advanced model) and their estimation of car travel times takes into account congestion but not parking (cf. our intermediate car model). Also in our data the modal disparity is larger if the intermediate car model is compared to the intermediate or advanced PT models than if the comparison is with the simple PT model. However, the difference between travel modes actually becomes smaller if both car and PT calculations are done at the most detailed level: in the advanced car model, park times considerably lengthen the total travel time, particularly in areas where public transport connections are at their best. Thus, the observed modal disparity in the advanced models becomes smaller than in the intermediate or simple models.

We further demonstrated that different parts of the study area get highlighted as areas for small/large accessibility disparity by the different models. Previous findings on modal accessibility disparity in an urban structure are to some degree controversial. Kawabata (2009) found the modal differences to be smallest in the downtown areas of Boston and San Francisco, and Elldér et al. (2012) demonstrated a similar pattern in Göteborg. In contrast, Hess (2005) found the modal difference in job accessibility to be higher among downtown residents in Buffalo and Niagara Falls than in the suburbs. In the Greater Helsinki area, the comparison based on the advanced models intuitively produced the most reliable results since it recognised both the city centre and the proximity of railway lines as zones of lower accessibility disparity and the outer ring road as a zone of higher accessibility disparity. Given the relatively strong city centre orientation of the current transit system in the Greater Helsinki area and the challenging parking conditions within the city centre area, it follows that our study area falls into the category of cities where the gap is smaller in the city centre than outside it.

7. Conclusions

Using conceptually corresponding models for car and PT travel time calculations is the key to achieving a more reliable analysis of modal accessibility disparity. Furthermore, the door-to-door approach in travel time calculations also makes the results truly comparable in absolute terms. In all, the most detailed analyses of accessibility disparity seem to be possible only with the more advanced models. Clearly, these models are also the most data hungry and accordingly, possibilities of using such models depend among other things on data policies of transport-related data providers. In our case, the European INSPIRE initiative (http://inspire.jrc.ec.europa.eu/) and general development towards openness in data policies among public administration have markedly increased the possibilities of analysing multi-modal transport. However, certain simplifications – such as the average park search times in our case – might be necessary if better data sources are lacking.

Requirements of the advanced PT model (e.g. inclusion of exact departure/arrival time and various route optimisation settings) may be overwhelming for a standard user to implement in a standard GIS. Thus, not only open data but also open route search interfaces (such as the Journey Planner API) providing the necessary algorithms and computational resources on servers, make such massive analysis feasible. Indeed, reliable spatial analyses of multimodal transport — which for long have been too data hungry and computationally intensive to calculate over large extents — are now more realistic for a larger group of researchers and practitioners than what they used to be.

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