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Spatial accessibility and transport inequity in Finland: Open source models and perspectives from planning practice

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ABSTRACT

During the last two decades, accessibility has begun to take a more central role in transport planning and decision making, as its importance has been recognized in many different policy agendas. Although environmental and social sustainability are central in contemporary public policy, the social exclusion effects related to access of opportunities are rarely measured at the national level. In this study, we analyze spatial accessibility to various opportunities in Finland at 1 km resolution and assess accessibility inequalities using the Palma ratio. Furthermore, we test how a web-based tool can be used in stakeholder communication and investigate the usefulness of the accessibility indicators and the tool for planning practice based on focus group discussions with Finnish transport planners. Our results show significant variation in the levels of access to different opportunities across Finnish municipalities. The Palma ratios reveal that the largest disparities are typically located in municipalities surrounding large city regions, where wealthier residents tend to have better access to opportunities compared to low-income populations. Finally, the insights from Finnish planning practitioners reveal that communicating national-level accessibility information via an online tool has high communicative and learning value for various planning and policy processes.

1. Introduction

Current lifestyles of most invidivudals are highly dependent on transportation and the increased travel demand over the past century has brought remarkable benefits for individuals and societies (Banister, 2011). At the same time, contemporary societies face an ongoing challenge to develop equitable mobility systems within the planetary boundaries (Ryghaug et al., 2023; Verlinghieri & Schwanen, 2020; Willberg et al., 2024). Spatial accessibility is one of the crucial factors influencing both environmental and social sustainability of transport systems. Accessibility assessment has been discussed in literature for several decades now (Hansen, 1959; Morris et al., 1979; Wachs & Kumagai, 1973). As such, there are many definitions for the concept of accessibility (Geurs & van Wee, 2004), but with *access* we refer here to the ease and capability to reach everyday destinations, such as services, jobs and leisure activities. Thus, accessibility provides a useful way to describe how a mobility system facilitates access for individuals to meet their daily needs, as well as an important goal for planning equitable transport systems where the distribution of benefits and burdens is taken into account (Martens, 2016; Martens et al., 2022; Pereira & Karner, 2021; Pereira, Schwanen, & Banister, 2017; Van Wee & Geurs, 2011).

Although various studies exist showing how different components of access can be measured and monitored on smaller scales (e.g., at a city level, or containing multiple cities), there are only few practical implementations for measures on national scales that take a distributional view on equity of access. The few existing national or global implementations tend to focus on the most urbanized catchment areas in key locations instead of looking at whole nations (Deboosere & El-Geneidy, 2018; Negm & El-Geneidy, 2024; Tomasiello et al., 2024; Wu et al., 2021). In addition, previous studies treat access as a friction model (i.e. generalized cost) where access is derived from land use characteristics and straight-line distances to locations instead of travel chains on transport networks (Weiss et al., 2018). The reasons for scarcity in national level studies are typically related to the lack of relevant data (e.g. public transport schedules, socio-demographic data, or relevant points of interest data), as well as high demand for computational resources to conduct national level analyses (Tenkanen et al., 2023). Furthermore, the larger the study area, the more complex gathering, handling and analyzing the data becomes.

Besides the need for national level studies, there is also a need for

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tools that support communication among various stakeholders in the planning process (Willson, 2001), combining quantitative and visual aspects that can show the relationships between accessibility of transport networks and specific places (Curtis & Scheurer, 2010; Kinigadner & Büttner, 2021). However, there are several institutional challenges related to embedding accessibility tools within the planning practice. For example, the authorities can be hesitant to define and measure accessibility, there can be a lack of agreement in terms of what is considered as sufficient level of access, and complicated administrative and governance structures can pose a further barrier for the use of accessibility information in planning processes (Ryan & Martens, 2023). In addition, there is a gap in understanding the usefulness and potential of accessibility information in planning practice (Papa et al., 2016; Papa et al., 2017). Despite some studies that have involved planning practitioners in evaluating accessibility tools (Bertolini et al., 2005; Curtis & Scheurer, 2010; Silva, Patatas, & Amante, 2017; Silva & Pinho, 2010), the number of studies evaluating the usefulness of accessibility information and tools for planning practice is very limited.

To close the implementation gap in planning practice, open source and transparent computational tools are seen as an integral aspect (Lovelace, 2021). Luckily, in recent years, there have been fast advancements in the transport modeling domain as various open source tools have emerged, making it easier and faster to analyze spatial accessibility by different travel modes (Alessandretti et al., 2022; Higgins et al., 2022; Lovelace, 2021). This is important, as proprietary and non-transparent models tend to create distrust among the public and stakeholders, leading to skepticism about the policies derived from them (Beukers et al., 2012; Morrison, 2018), and resulting in a less democratic process.

Stemming from these starting points, this study focuses on open data and open source accessibility tools to examine spatial accessibility across Finland at the national level. As a case study, we investigate access to various opportunities in Finland using nearest facility analysis, cumulative opportunities measure, and Palma ratio as a measure of accessibility inequality. Furthermore, we developed an interactive online tool to communicate the results of our study to stakeholders, and assess the usefulness of the tool and accessibility data for planning practice based on focus group discussions with Finnish transport practitioners and planners.

2. Background and related work

2.1. Finnish mobility and planning system

According to data from the Finnish Environment Institute (2024), 1.1 million people in Finland live in the car city fabric of urban regions and 0.73 million in sparsely populated areas. Thus, altogether one third of the population lives in these two highly car-dependent areas. In addition, car travel has a dominant role in the Finnish transport system regardless of the region, as 62 % of trips and 84 % of kilometers traveled domestically were made by car (Kallio & Kärkinen, 2023). Transport poverty is in many parts related to car use or car dependence. Despite the clear targets set in the Finnish governance system, such as decarbonization goals (Kotilainen et al., 2019) or the promotion of walking, cycling and public transport (as studied in this paper), there is a clear implementation failure in actual planning and policy-making processes (Hytönen et al., 2016). Similar to recent findings from Sweden (Witzell, 2020), present day Finnish institutions are not able to envision and implement alternative path-breaking plans and policies (e.g., road pricing, parking restrictions, low emission zones, and public transport investments) that could achieve climate and equity goals.

The Finnish planning system works within the model of a Nordic democracy. Based on legislation, Finland's planning system is hierarchical, meaning that the regional land-use plan is the highest plan, with which municipal land-use plans must not conflict. Detailed plans, in turn, must comply with the municipal land-use plans. Municipalities rarely have a separate transport plan, but instead, transport system components are part of regional and municipal plans. On the national level, there is no land use plan, but rather National Land Use Objectives, while recent years have seen the development of the National Transport System Plan, with a 12 year horizon. Another important recent development of the planning legislation has been the introduction of MAL agreements (Maankäytön, asumisen ja liikenteen sopimukset, meaning "land use, housing and transport contracts" in English). Defined for specific urban regions in Finland, MAL agreements are intended as an instrument to incentivize coordination of regional land-use, housing and transport policy (Bäcklund et al., 2018, 2023).

There are two main overarching challenges in the Finnish planning practice. On the one hand, planning practice in Finland still relies on its version of 'predict and provide' planning approach, largely centered on forecasting as continuation of the past trends and the assumptions of satisfying travel demand that relies on the growth of car-based mobility and GDP (Moilanen et al., 2022). These existing traffic forecasting models, combined with cost-benefit analysis, are intertwined with Statistics Finland's population forecasts or population forecasts done by the municipalities, as well as job development forecasts in different economic sectors, which usually anticipate optimistic growth trends. The intertwined set of these planning tools and underlying assumptions reinforce a practice where path-breaking mobility futures are usually not envisioned in official planning processes (Mäntysalo et al., 2023). On the other hand, these underlying assumptions and practices are intertwined with multi-level and multi-actor discoordination of actions, underpinned with a decade of administrative reorientation and restructuring across key mobility sector actors. For example, despite the statutory hierarchy, there is often an asymmetrical distribution of powers in practice, in which municipal planning is more powerful than regional planning (Purkarthofer & Mattila, 2023). Finally, despite the intention of MAL agreements, these planning processes have issues related to public participation and conflicts between municipalities (Bäcklund et al., 2018, 2023).

2.2. Implementation challenge - practitioners' perspectives on accessibility tools

Despite the fact that accessibility has begun to take a more central role in transport planning (Boisjoly & El-Geneidy, 2017b; Lucas, 2012), the implementation challenge of accessibility tools highlighted by Ventura (1995) in the 90s and Curtis (2008) in the 2000s still remains. Overall, the change in planning practice has been relatively slow (Handy, 2020). One core barrier for addressing this implementation gap has been the development process of the tools themselves (Curtis & Scheurer, 2010). Overall, accessibility tool development has been plagued by the discrepancy between the tools needed in practice and the tools developed in research (Kinigadner & Büttner, 2021; Papa et al., 2017; Silva, Bertolini, et al., 2017). Thus, there has been a disbalance between the scientific rigor and soundness on the one hand, and practical relevance and usability on the other hand. This disbalance has been partly related to lack of transparency of developed tools, as they are often perceived as "black boxes" by planning practitioners. In response to these challenges, previous research has suggested co-creating simpler and open-access tools, with accompanying open access datasets (Boisjoly & El-Geneidy, 2017a; Kinigadner & Büttner, 2021). Moreover, previous research has suggested streamlining indicators, catering for different user needs, and in general understanding the communicative needs in planning practice while formulating the tools (te Brömmelstroet et al., 2016).

Besides the more specific usefulness and usability challenges, the implementation challenge has been plagued by the broader institutional barriers (Curtis & Scheurer, 2010; Geurs & Halden, 2015; Ryan & Martens, 2023; Sunio et al., 2023). On the one hand, institutional barriers relate to lack and differences in knowledge (Boisjoly & El-Geneidy, 2017a; Ferreira & Papa, 2020; Ryan & Martens, 2023). Overall, understanding of accessibility in planning practice has been rather superficial without consensus. Besides conflict in interpretation of accessibility itself, existing planning cultures have a conflicting tradition, as they are still dominated by the knowledgebase from neoclassical economics, best exemplified with the use of cost-benefit analysis. On the other hand, besides the knowledge issue, institutional barriers include lack of time, financial resources, organizational support and regulatory frameworks to implement accessibility evaluation (Boisjoly & El-Geneidy, 2017a; Ferreira & Papa, 2020).

2.3. Evaluation of accessibility and transport equity

Accessibility measures are typically developed based on four main approaches: i) cumulative opportunities, ii) gravity, iii) utility, and iv) space-time (Geurs & van Wee, 2004). Each of the four main approaches has its own advantages and disadvantages. Cumulative opportunity measures and gravity measures primarily focus on transport and land use by examining spatial distribution of opportunities, while utility and space-time measures adopt a more heterogeneous approach, including household preferences and traveler perceptions, which adds to their complexity (Siddiq & Taylor, 2021). More complex calculations and copious data requirements make it a difficult task to look at spatial disparities across large geographical coverage or to communicate the results with planners and decisionmakers.

Cumulative opportunity-based measures are one of the most used approaches to analyze accessibility in research and practice, as they are simple to interpret, and rather simple to compute as the sums of all potential opportunities reached within a given travel time threshold (El-Geneidy & Levinson, 2022; Levinson & King, 2020). On the other hand, the disadvantages of cumulative opportunity measures lie within the difficulty in choosing meaningful travel time cutoff thresholds and the lack of decay functions, i.e. diminishing effect of distance or travel time (Kapatsila et al., 2023). Using a cumulative metric means a constant, equal weight is applied to every opportunity accessible within the specified time window. While cumulative-opportunity measures are not as theoretically sound as gravity-based measures, they have been shown to have a strong correlation with such measures, making them a reliable indicator of regional accessibility (Boisjoly & El-Geneidy, 2017a; Kapatsila et al., 2023; Palacios & El-geneidy, 2022). Despite the similarities in performance between cumulative-opportunity and gravity-based approaches, previous research shows that different accessibility measurement methods may yield different analytical results e.g. when measuring changes in access before and after transport interventions (Klar et al., 2023) or when assessing equity of access using space-time methods which might lead to more conservative estimates of equity (Neutens et al., 2010).

Assessing social disadvantage is one of the areas in which accessibility plays a crucial role (Pereira, Schwanen, & Banister, 2017). Social disadvantage is commonly analyzed based on different approaches (see Willberg et al., 2024 for a review), such as *disparity analysis* that compare the levels of access between population groups or areas with distinct characteristics (e.g. Bocarejo & Oviedo, 2012; Deboosere & El-Geneidy, 2018; El-Geneidy et al., 2016; Järv et al., 2018; Liu & Kwan, 2020), or based on *sufficiency analyses* that assess the accessibility of individuals or groups against normative judgements of minimum thresholds (Allen & Farber, 2019; Lucas et al., 2016; Martens et al., 2022), or that aim to identify spatial gaps in accessibility to a certain activity or service (e.g. Allen & Farber, 2020; Widener et al., 2015). Disparity analyses can be used to explore potential causes for subpar accessibility and potential biases in transport policies, where one group carries systematically more accessibility insufficiency than others. However, Martens et al. (2022) have proposed a shift from disparity analysis towards sufficiency analysis, arguing that disparity analysis falls short by potentially masking underlying inequities. Sufficiency analysis can offer more nuanced measures to understand equity-related questions by focusing on whether accessibility levels are sufficient for specific population groups. However, the challenges of sufficiency analyses relate e.g. to the availability of high-quality granular data, as well as the difficulty in defining the criteria for what constitutes as "sufficient". Thus, disparity analysis can be useful and more practical especially when covering large geographical areas and varying contexts.

One of the typical measures to understand inequalities in access includes the Gini coefficient and Lorenz curve, which are used to visualize inequalities in transport (Lucas et al., 2016; Pritchard et al., 2019). Although the Gini coefficient assesses the deviation of access in a hypothetical situation in which everyone has the exact same level of access (i.e. emphasizes equality), it does not provide specified insights into different population groups and differences of their accessibility level (Karner et al., 2024). Thus, in more recent literature some alternative inequality measures have gained traction, such as the Palma ratio, which is better suited for visualizing the extremes of inequalities according to recent studies (Banister, 2018; Karner et al., 2024). In addition to Palma ratio, there are other inequality and poverty measures, such as the 20:20 ratio, Concentration Index, Theil T and Foster-Greer-Thorbecke measures.

Palma ratio provides a nuanced understanding of how accessibility is divided between the richest and the poorest segments of the studied population (Karner et al., 2024; Pritchard et al., 2019). It can also be more easily communicated, providing a better platform for planners and decision makers to understand inequalities in access (Karner et al., 2024), which is also the reason why we use Palma ratio in our study. In the context of transport studies, the Palma ratio is described as a ratio of average accessibility of the wealthiest 10 % to average accessibility of the poorest 40 % (Karner et al., 2024). Many of these inequality measures have been directly incorporated into the functionality of available open source software that can be used to evaluate accessibility (Klumpenhouwer, 2024; Pereira & Herszenhut, 2023).

2.4. The role of open source tools in transport planning

The wider adoption of more open analytical approaches in science and practice has been driven by a rapid growth of free and open source software. A growing number of promising transport related open source tools have emerged, giving alternatives to their traditional closed source / commercial counterparts (Alessandretti et al., 2022; Lovelace, 2021). Open transport models and tools can be a significant leverage point in the planning process as they provide transparent, robust and actionable evidence that is available, not only for professional transport planners, but to a range of stakeholders including decision makers, scientists as well as interested citizens (Lovelace et al., 2020). Luckily, a plethora of open source tools have been introduced to perform various transport-related tasks, including network routing and spatial accessibility calculations at different levels (Alessandretti et al., 2022; Lovelace, 2021). Analyzing different transport phenomena typically requires a set of tools in the analytical process. Picking the right tool typically depends on the question or objective at hand, as well as the type and availability of data (Lovelace, 2021; Tenkanen et al., 2023).

Tools often emphasize different aspects and functionalities for geographical transport analysis. Alessandretti et al. (2022) classify the main transport-related open source tools into five different categories based on their functionality. The five categories encompass the most general tools that are used to validate networks; display networks; analyze transport networks; analyze multilayer networks; or which are used for routing or accessibility evaluations. Some of these tools are more comprehensive in nature which is the category of tools we employ in this paper. These tools provide possibilities to conduct multimodal routing and compute travel time matrices, such as *OpenTripPlanner, r5r* and *r5py* (Fink et al., 2022; Morgan et al., 2019; Pereira et al., 2021), or provide functionalities to analyze spatial accessibility and transport equity based on different measures including tools, such as *accessibility* library for R (Pereira & Herszenhut, 2023) and *access*, *UrbanAccess,* and *traccess* for Python (Blanchard & Waddell, 2017; Klumpenhouwer, 2024;

Saxon et al., 2022). In conclusion, these tools provide new possibilities for planners and decision makers to evaluate the impacts of their decisions on transport equity.

3. Data and methods

3.1. Study design

Fig. 1 gives an overview of our study workflow consisting of four main steps. First, we gathered the input data for the accessibility analyses covering the statistical grid cells as the origin locations, seven different opportunity types as the destination locations, and transport network data that is needed for creating a routable network for accessibility analyses based on cycling and transit. In the second step, we conducted the accessibility analyses for the selected opportunity types in Finland and computed three accessibility indicators: i) cumulative opportunities metric (i.e. how many particular opportunities are accessible within a predetermined travel-time), ii) nearest facility metric (i.e. minimum travel time to closest opportunity comparing cycling and public transport accessibility against each other focusing on educational facilities), and iii) Palma ratio indicator, i.e. the equity of access based on income and accessibility conducted at a municipality-level based on the cumulative metrics. In the third step, we developed an online visualization tool that we use to communicate and share our accessibility indicators to Finnish transport practitioners. The final step focused on assessing the usability of the accessibility indicators and the online tool for planning practice based on focus group discussions with Finnish transport practitioners. More details about each of these steps are provided in the following sections.

3.2. Socio-demographic data - origins

Table 1 contains the key datasets used in this study. As the origins of the trips in our analysis, we use a national level statistical population grid provided by Statistics Finland which is aggregated into 1 km × 1 km cells (Statistics Finland, 2023). The national grid data only contains cells that have geolocated information about population structure and, in total, the dataset consists of 157,784 cells. The data includes a variety of population attributes that describe the population on a cell level, most importantly the population count and income data that we employ in this study. The centroids of the grid cells were used as the exact origin locations for the modeling task. We chose to use data at 1 km resolution for a couple of reasons: 1) Statistics Finland provides this level information openly for anyone, making it possible to reproduce most of our results. The income attribute is not open access at 1 km resolution (which we used), but it is shared openly at postal code level. 2) We also wanted to control the computational load because we conduct analyses at a national level and consider various opportunity types and accessibility measures.

3.3. Opportunities - destinations

We selected a set of opportunities that align with the basic needs of human beings, in accordance with the view of Rawlsian philosophy on primary social goods (Martens, 2016; Rawls, 1982; Van Wee & Roeser, 2013). The opportunity types that we used are: jobs, educational

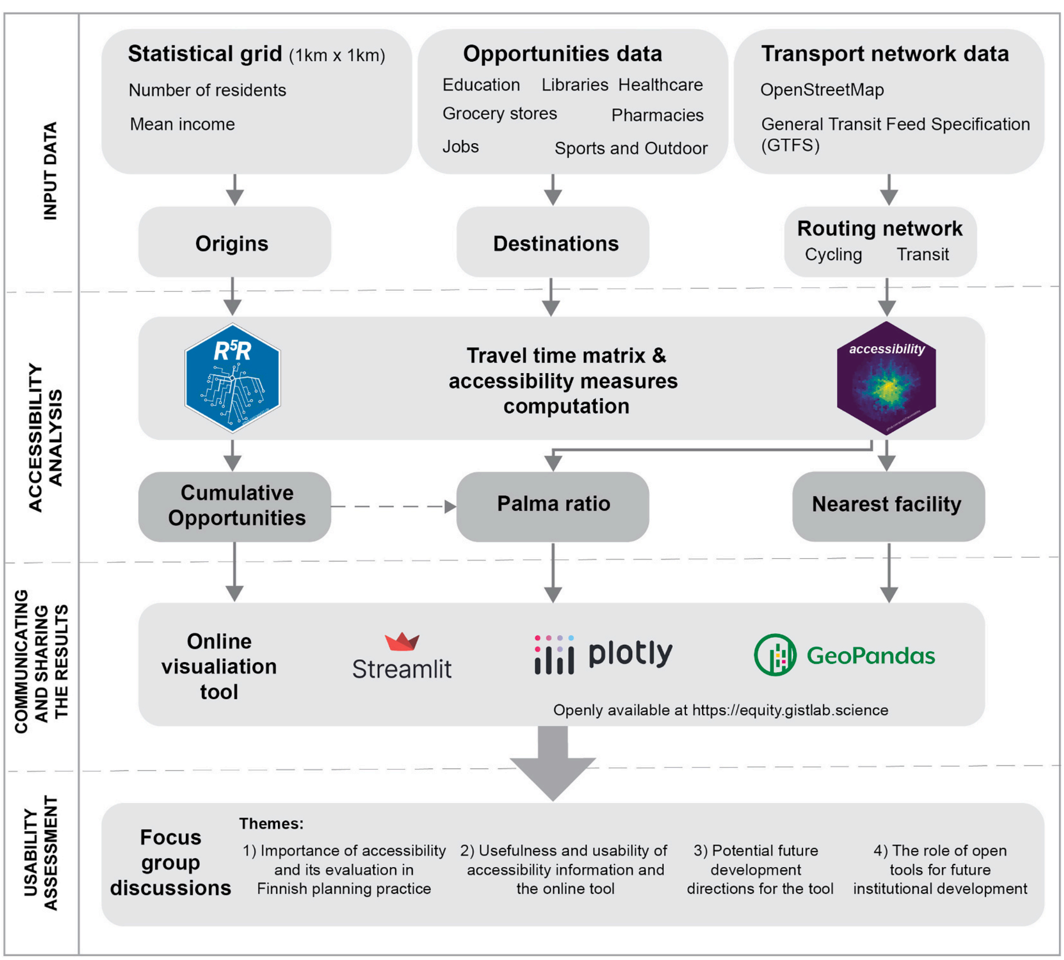

Fig. 1. The study workflow includes four main parts: i) gathering relevant datasets, ii) calculating the accessibility indicators, iii) communicating our results with an online visualization tool, and iv) assessing the usability of the accessibility information and the online tool for Finnish planning practice.

Table 1
Key datasets used in this study.

Data	Purpose	Availability	Data producer
Population grid 1 km × 1 km	Origin / Socio-demographic data (population counts, income)	Mostly open access	Statistics Finland
Jobs (2019)	Destination / opportunities	Chargeable product	Statistics Finland
Educational facilities (2021)	Destination / opportunities	Open access	Statistics Finland
Hospitals and Clinics (2021)	Destination / opportunities	Open access	Finnish institute of health and welfare
Libraries (2022)	Destination / opportunities	Open access	OpenStreetMap contributors
Outdoor activity or sports facilities (2022)	Destination / opportunities	Open access	University of Jyväskylä
Grocery stores (2022)	Destination / opportunities	Web data extraction / Open access	Lidl, Kesko, M group, S group
Pharmacies (2022)	Destination / opportunities	Web data extraction / Open access	Association of Finnish pharmacies
OpenStreetMap	Street network used for walking and cycling	Open access	OpenStreetMap contributors
General Transit Feed Specification (GTFS) data	Public transport data (schedules, routes, stops, etc.)	Open access	Traficom

facilities, hospitals and clinics, libraries, outdoor activity or sports facilities, grocery stores, and pharmacies (Table 1). In terms of grocery stores and pharmacies, we gathered a consistent dataset directly from their websites using web scraping with Python's selenium library (Selenium, 2022). We extracted the name of the store, address information and opening hours and geocoded the list of addresses with Python's geopandas library (Jordahl et al., 2022) into spatial data format using the Nominatim geocoding API (Nominatim, 2022). We furthermore manually went through the addresses to ensure the quality of the data and fixed possible errors in the store locations or missing information. The number of jobs provided by Statistics Finland were readily aggregated into the spatial grid cells. Lastly, we merged the opportunity data with the national grid using a spatial join operation in geopandas library. In the calculations, we use the centroid of the grid cell as destination. For the educational services, the exact point geometry of each educational facility is used as a destination for more precise results related to the nearest facility analysis.

3.4. Transport network data

To calculate the travel times by different travel modes, we acquired two datasets: street network data from OpenStreetMap in Protocol Buffer Binary (PBF) format, and the transit schedule data in General Transit Feed Specification (GTFS) format. OpenStreetMap PBF data contains different tags to categorize routes used by different modes in the routing algorithm. The national level OpenStreetMap PBF data for Finland was downloaded from the (Geofabrik, 2023) website. For the transit schedule data, we used a GTFS dataset that covers all transit modes. The data was provided by Fintraffic which is operating under the Ministry of Transport and Communications of Finland, while the data quality was validated and partially improved by the Finnish Environment Institute.

3.5. Travel time matrix calculations

For calculating the travel times by different travel modes (cycling, public transport), we used the *R5* routing engine (Conway et al., 2017, Conway, Byrd, & Eggermond, 2018) and its *r5r* wrapper (Pereira et al., 2021) for the R software (v4.2.2). We chose to use *R5* because it is currently the only routing engine that is able to handle massive travel time matrix computations, such as ours (Higgins et al., 2022). Travel time is the most commonly used cost of travel in accessibility studies (Willberg et al., 2024) because of its relevance to daily life of people, which is also the reason why we use this metric in our accessibility analyses. We calculated the travel times between all selected origins and destinations in Finland by different travel modes which we later used to construct the accessibility measures. Table 2 includes further details about the parameters used in our analyses (also see Supplement S1 for computational details).

Public transport travel time computations were done using the schedules of Wednesday 7th of June 2021 considering the following transit modes: tram, subway, rail, bus, ferry, cable car, gondola and funicular. We apply a 30 min departure time window and calculate the travel times at 07:00–07:30 am for work and education related trips, and 10:00–10:30 am for other trips. The time window parameter is used because there can be significant variation in the resulting travel times depending on the departure time due to the temporal variations in the level of service of the public transport. By default, r5r calculates accessibility for each minute inside this 30 min time window up until the set cut-off threshold, returning an average of these departure times.

Travel time computations by cycling were done assuming a constant cycling speed of 15 km per hour which was selected based on previous studies about typical cycling speeds (Aldred et al., 2017). We also consider the level of traffic stress (LTS) because it allows to generate travel times that are more representative to actual routes taken by cyclists compared to simple shortest paths (Mekuria et al., 2012). This concept has been adapted to the R5 routing engine to categorize different bicycle routes based on their stress levels (Conway et al., 2017). In our case, we selected the LTS 2 level which is considered as tolerable for the mainstream adult population, preferring streets where cyclists have dedicated lanes and only have to interact with traffic at formal crossing (Conveyal, 2024).

3.6. Calculating the accessibility indicators

To calculate the accessibility indicators for different opportunities by cycling and public transport, we used *r5r* and *accessibility* libraries. The travel times between origins (population grid) and destinations (opportunities) were calculated with *r5r* (Pereira et al., 2021) which were then transformed into selected accessibility measures using the *accessibility* library that offers a set of fast and convenient functions to help conducting accessibility analyses (Pereira & Herszenhut, 2023). To enable reproducibility of our results, we share the R codes used for computing our accessibility measures at: https://github.com/AaltoGIS/CEUS-Equity-of-access.

Table 2
Key parameters used in our accessibility analyses.

Mobility attribute	Parameter
Cut-off threshold	30, 45 and 60 min
Travel modes	Transit, Cycling
Date of the travel	Wed 7th June 2021
Departure time for workplaces and education	Time window 7–7:30 am
Departure time for other opportunities	Time window 10–10:30 am
Maximum transfers per PT trip	1
Maximum distance one will walk to access, egress or transfer on a public transport trip	1 km (for each leg of the journey)
Walking speed	3.6 km/h
Cycling speed	15 km/h (walking speed for network sections that exceed the set LTS value)
Level of traffic (LTS) stress tolerated by cyclist	2: Tolerable for the mainstream adult population.

The nearest facility analysis was used to construct the accessibility by proximity indicator. The indicator was created by first calculating the travel times with *r5r* that were then used to find the closest educational facility for each origin based on travel time using the *accessibility* library. This information was then combined with population count data and that allowed us to calculate the share of population that can reach the facilities with a given travel time (at a minute-by-minute basis). As a final step, we plotted these results as a line graph that show the share of population against the time traveled to reach the destination (see Figs. 3 and 6). We conducted the nearest facility analysis to provide an easily understandable system-level indicator that gives an overview of how long it typically takes to reach a specific opportunity, providing useful contextual information about the level of service in a given municipality (Tenkanen et al., 2016).

We used *r5r* library to compute the cumulative opportunities measure (Eq. (1)) by using the Hansen equation (Hansen, 1959) that counts the number of opportunities accessible from each location considering a maximum travel time cutoff (Levinson & King, 2020):

$$A_i = \sum_j O_j f(C_{ij}) \tag{1}$$

here A_i is the access from location i, O_j is the number of opportunities available at destination j, C_{ij} is the cost of travel from i to j, and $f(C_{ij})$ is the impedance function. The impedance function (Eq. (2)) returns value 1 if the travel time is less than a given threshold t and a value 0 otherwise:

$$f\left(C_{ij}\right) = 1 \text{ if } C_{ij} \leq t, \text{else } f\left(C_{ij}\right) = 0 \tag{2}$$

We use the cumulative opportunities measure due to its communicability and consistent results across different geospatial settings. The measure is also appreciated by most decision makers as its components are easy to understand (El-Geneidy & Levinson, 2022; Levinson & King, 2020). To mitigate the arbitrariness of edge effects (Levinson & King, 2020), we considered three thresholds (30, 45 and 60 min) instead of using a singular cut-off threshold.

Due to the limitations in Gini index (see Section 2.3), we use Palma ratio as a measure of accessibility inequality. The Palma ratio (P) measures the average accessibility of the residents living in the wealthiest 10 % (A_{top10}) areas divided by the average accessibility of the residents living in the poorest 40 % ($A_{bottom40}$) (Pritchard et al., 2019):

$$P = \frac{A_{top10}}{A_{bottom40}}$$

The Palma ratio was calculated at municipality level based on accessibility and statistical data associated with 1 × 1 km grid cells. The calculations were done using the *accessibility* library. When computing the Palma ratio, we consider the i) cumulative access of opportunities by public transport and cycling based on Hansen equation (as described previously), ii) mean income per capita within each grid cell, and iii) the population, i.e. the number of people living in each grid cell. The population data is used to weigh the accessibility levels for the poorest and wealthiest groups that ensures that areas with larger populations have a proportionately larger impact on the average accessibility measure.

A higher Palma ratio indicates greater equity difference in access when the income changes. Values higher than 1 indicate that the top 10 % income residents have better access than the bottom 40 % income residents. Values below 1 indicate that the bottom 40 % income residents have better access and a ratio of 1 indicates that the access is at an equilibrium. In some cases, the Palma ratio can be 0 which indicates that the top 10 % income residents do not have any opportunities accessible within a given travel time threshold, whereas the value *inf* (infinite) means the same thing for the bottom 40 % income group respectively.

3.7. Interactive online tool for communicating and visualizing the results

For communicating our results, we developed a dedicated online tool with an easy-to-use user interface that consists of multiple interactive pages with maps and graphs. The users can investigate and compare:

1. The spatial distribution of opportunities on a map in Finland. The opportunities can be explored at a national level or in selected municipalities (Fig. 2).
2. The accessibility of educational facilities in Finnish municipalities (Fig. 3) shows the cumulative share of the population aged 7–17 against the minimum travel time required to reach the nearest educational facility, either by cycling or public transport.
3. The cumulative number of opportunities accessible by public transport or cycling in municipalities across Finland (Fig. 4). Users can select their area of interest, the type of opportunity, and the travel time cut-off threshold. The result will be displayed as a map showing the distribution of access to the selected opportunity.
4. The equity of access between different municipalities in Finland based on Palma ratio (Fig. 5). Users can select the travel mode, as well as the opportunity type that they want to investigate.

The tool was built using various Python libraries: *streamlit* (v0.12.0) library (Streamlit, 2023) for developing the user interface components, *plotly* (v5.14.1) library (Plotly, 2023) for creating the data visualizations and maps, and *geopandas* (v0.11.0) library (Jordahl et al., 2022) for data processing. The application runs on top of NGINX (v1.18.0) web server (NGINX, 2023) that is hosted at CSC IT Center for Science Finland. The source codes for the online tool are openly available at: https://github.com/AaltoGIS/Equity-of-access-Finland.

3.8. Focus group discussion with planning practitioners

To explore and understand the perspectives on evaluating accessibility, the usability of our online tool, as well as the institutional barriers in the Finnish planning practice, we organized two focus groups in October 2023. We chose to use focus group discussions as a qualitative method because it allows rich exploration of diverse factors, as discussions involve group dynamics and mutual building upon expressed ideas over time (Barbour, 2007). Similarly, previous research focused on specific case studies has used qualitative methods for exploratory purposes (Curtis & Scheurer, 2010; Ferreira & Papa, 2020; Göçmen & Ventura, 2010; Kinigadner & Büttner, 2021; Ryan & Martens, 2023; Sunio et al., 2023).

One focus group was conducted with planners from municipal-regional planning levels, while the second focus group was done with national level planners. The participants ($n = 6$) represented the city and regional transport authorities, the Ministry of Transport and Communication, and the Finnish Transport and Communications Agency. Thus, the sampling of the focus group participants can be considered as representative of the key stakeholders in the Finnish transport planning practice.

Before the focus group discussions were held, participants received a short 15 min video recording explaining how the tool can be used, which accessibility measures are included in the tool, as well as a list of discussion topics for the focus group session as: i) evaluating accessibility in the past planning processes, including the reasons for evaluation, use cases, and challenges faced (e.g. skills, precision, accuracy); ii) usability of the tool and the indicators (i.e., understanding the accessibility information, and using it to support discussion among stakeholders); iii) perspectives on the importance of open access, reproducibility, costs, flexibility, trust, ownership and maintenance of the tool; and iv) future needs as well as changes needed within the broader institutional setup, such as integration between land use and transport planning, power redistribution, etc.

We recorded and coded the transcripts of the discussions, followed by organization of codes in overarching themes (Barbour, 2014). This inductive coding was first done by the primary coder, followed by a verification by two secondary coders. We identified four themes based

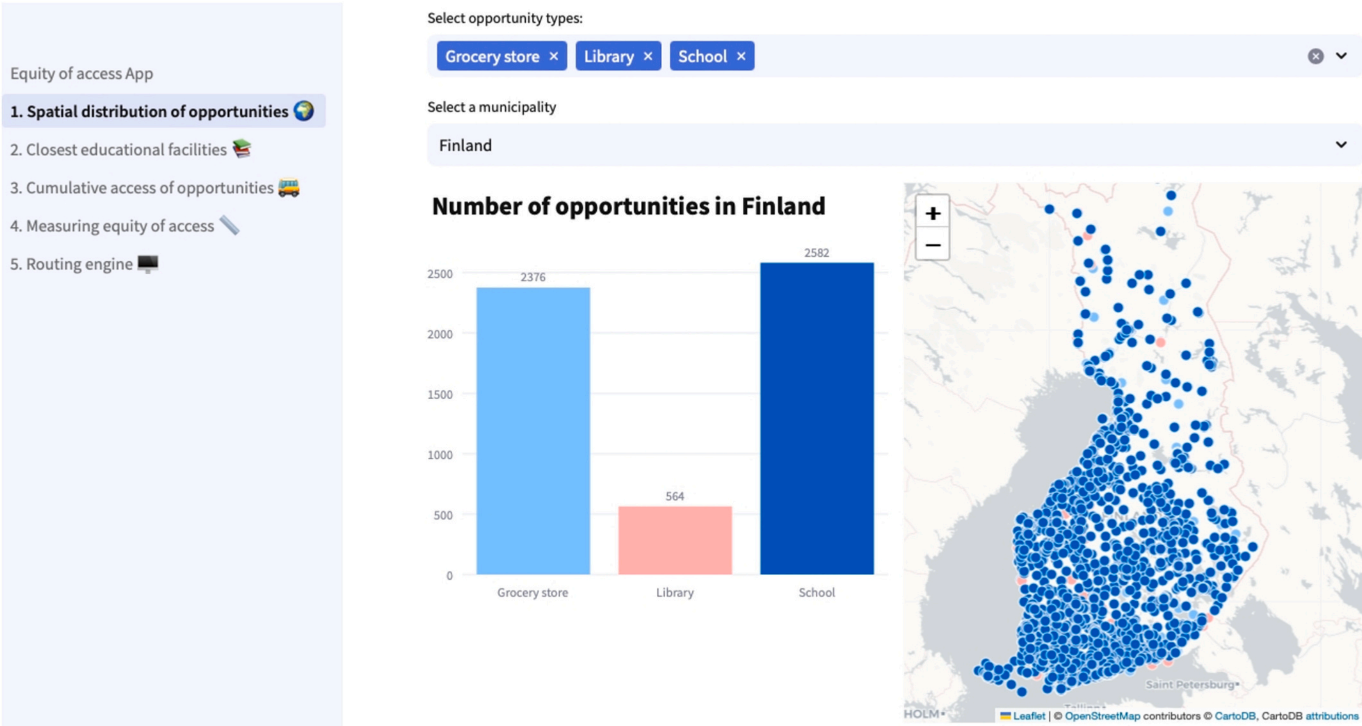

Fig. 2. The user interface allows exploring the locations of different opportunities in any Finnish municipality.

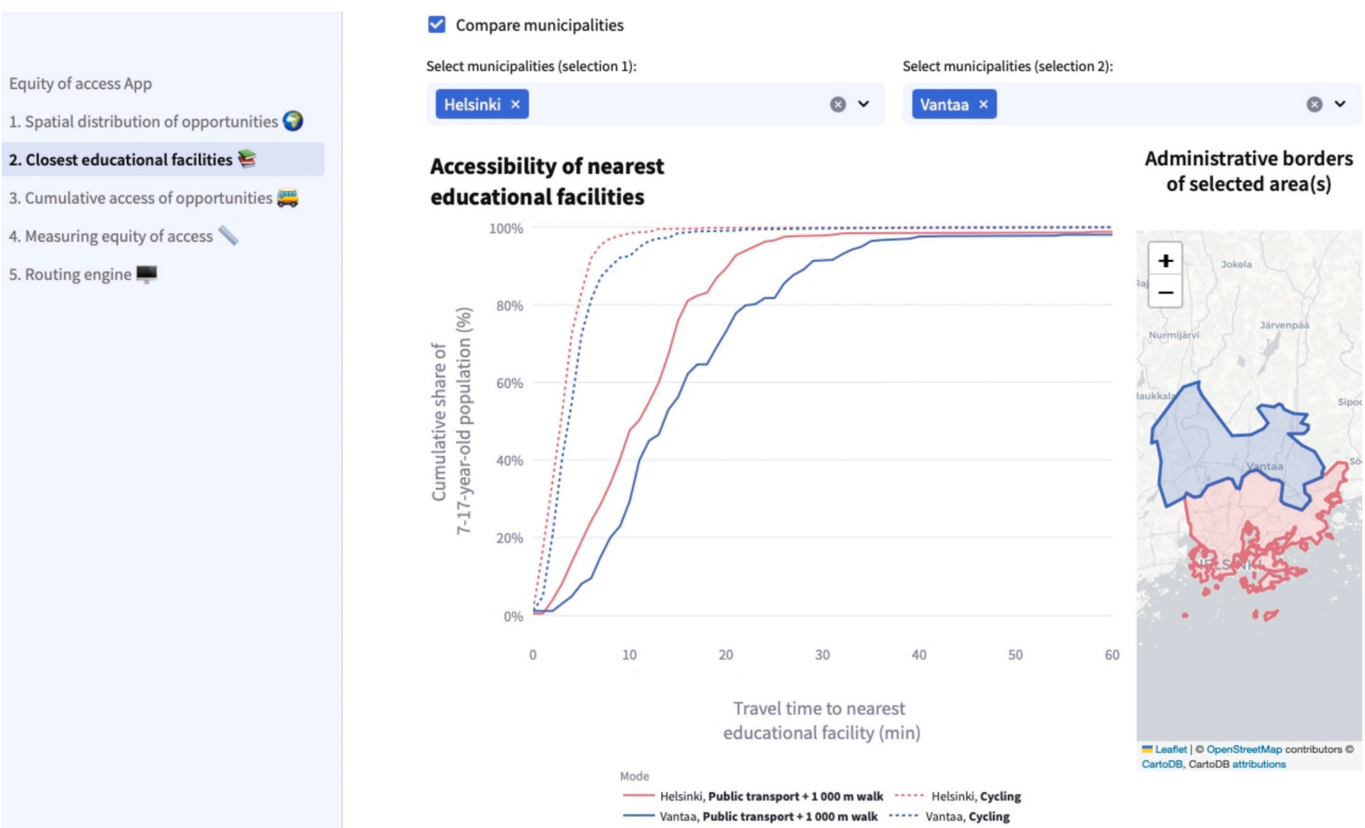

Fig. 3. The tool allows the user to explore and compare the accessibility of nearest educational facilities easily in any Finnish municipality showing the cumulative share of students reaching the closest school in given travel time.

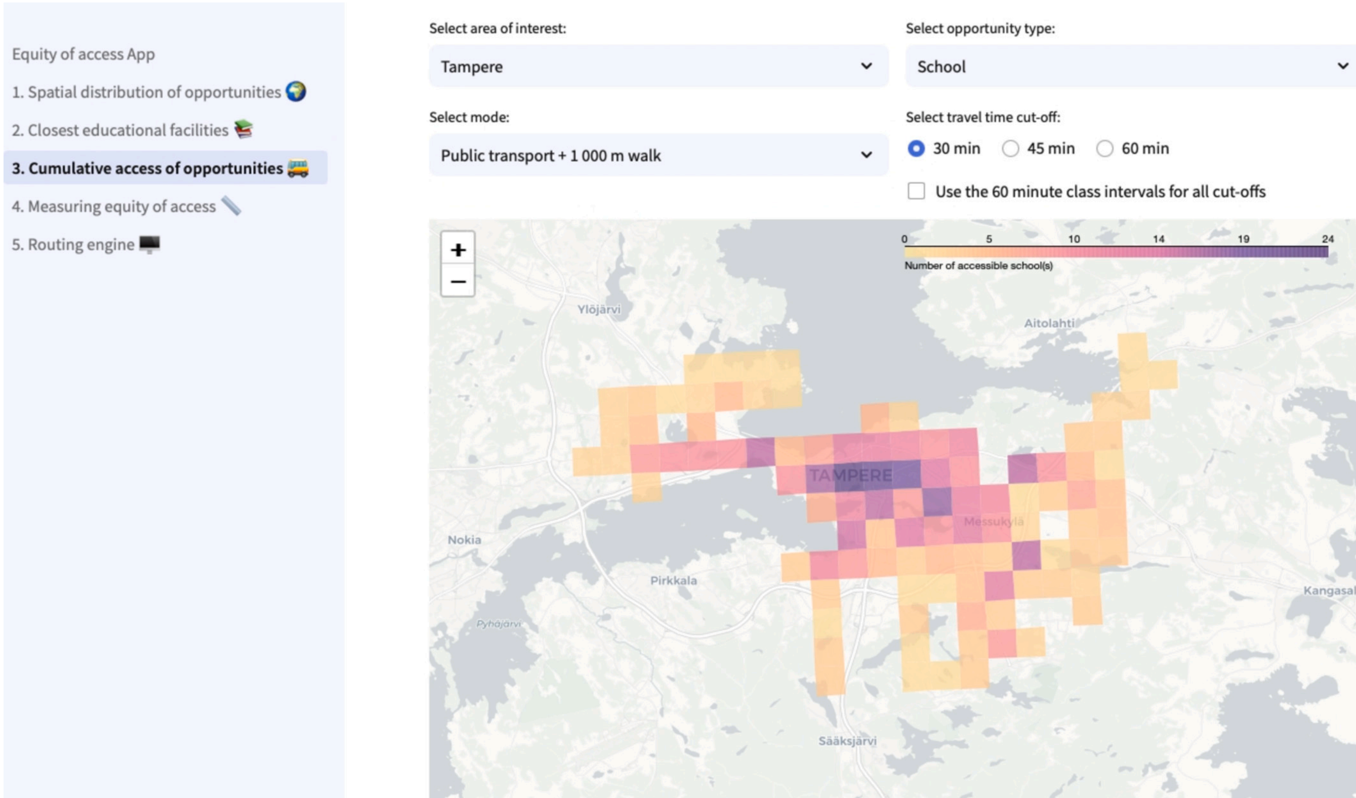

Fig. 4. The tool makes it possible to explore and compare the cumulative number of opportunities accessible by public transport or bicycle in different municipalities across Finland.

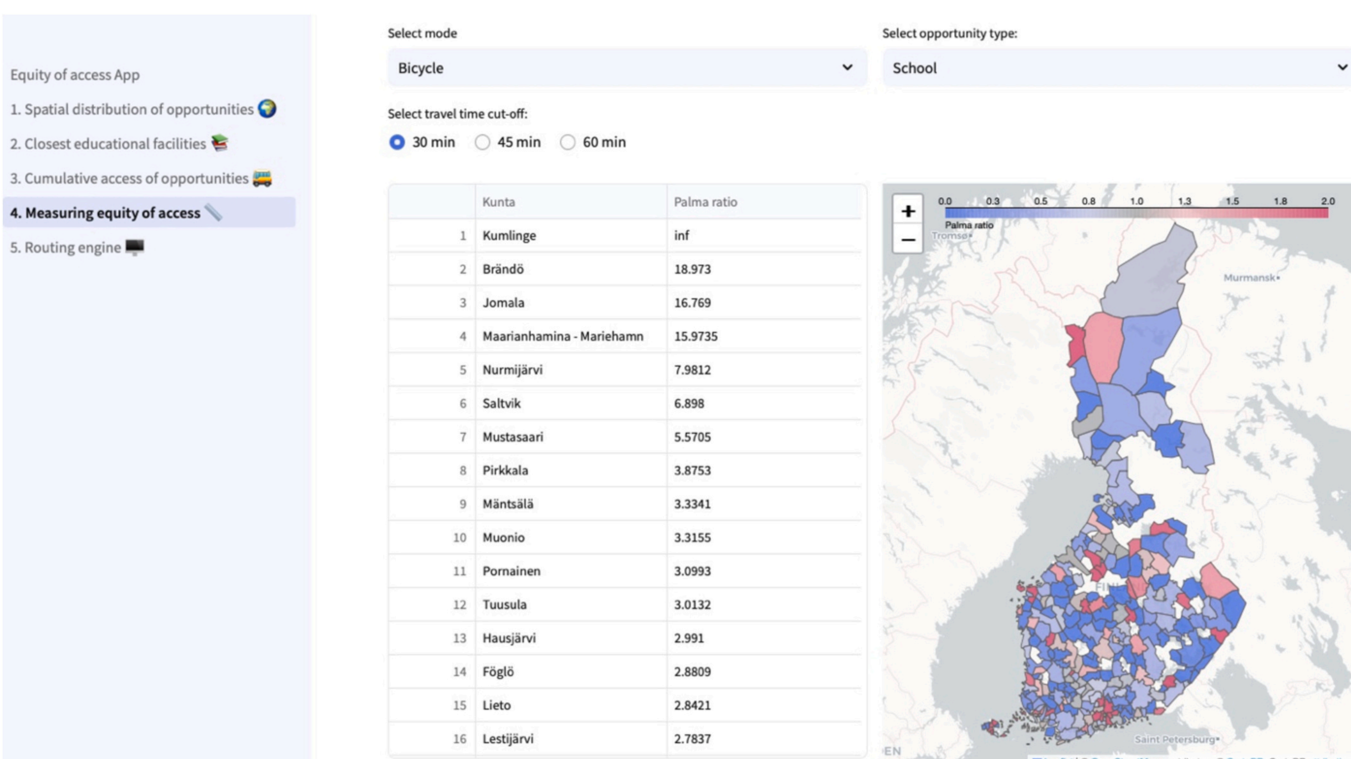

Fig. 5. The tool makes it possible to compare and visualize the equity of access between different municipalities in Finland, by using Palma ratio. The interface also provides a list of Palma ratios for all Finnish municipalities ranked from highest to lowest.

on the discussions (see section 5) by reaching re-coding saturation (Barbour, 2014).

4. Results

4.1. Variations in the level of access in Finland

Our results represent various national level accessibility metrics for several different opportunity types. Overall, our results cover 264 municipalities in Finland. In the following, we highlight some key findings for specific areas in Finland based on our analyses. Due to the large scale of our analysis, a dedicated online tool that can be used to explore the accessibility indicators in any Finnish municipalityis available at https://equity.gistlab.science.

Fig. 6a shows the travel time to the closest educational facility with either cycling or public transport against the cumulative share of the 7–17-year-old population in Finland that fall into a given travel time catchment area. In Fig. 6b, we show the same metric for the capital region, whereas Fig. 6c and d show individual modes and reveal the relative access differences between the largest city regions in Finland. When comparing cycling and public transport access on a national level, cycling tends to yield far greater distribution of access in relation to population. This is not surprising as there are fundamental differences in how the two modes are organized and distributed. Due to its sparse population, Finland has significant differences in access across various locations, opportunity types and transport modes. These differences are evident in Fig. 6d, where the disparities between four locations are clearly visible even though we are looking at some of the largest cities in Finland. Even though the city of Oulu is the 5th largest city in Finland, its population density is much lower than other large cities due to its sprawling land use and larger geographic area. In some degree, this explains why its access levels are lower than the other three cities.

Fig. 7 shows the spatial distribution of cumulative access to educational facilities within 30 min in Finland and a close-up of the capital region. The number of accessible opportunities provides evidence of how equitable the distribution of access is for a given location. Here, the differences between the two modes are evident: the map depicting public transport appears quite empty, while the one for cycling is much more widespread. Approximately 64 % of the total population in Finland can access most of their daily opportunities by cycling in 30 min, while

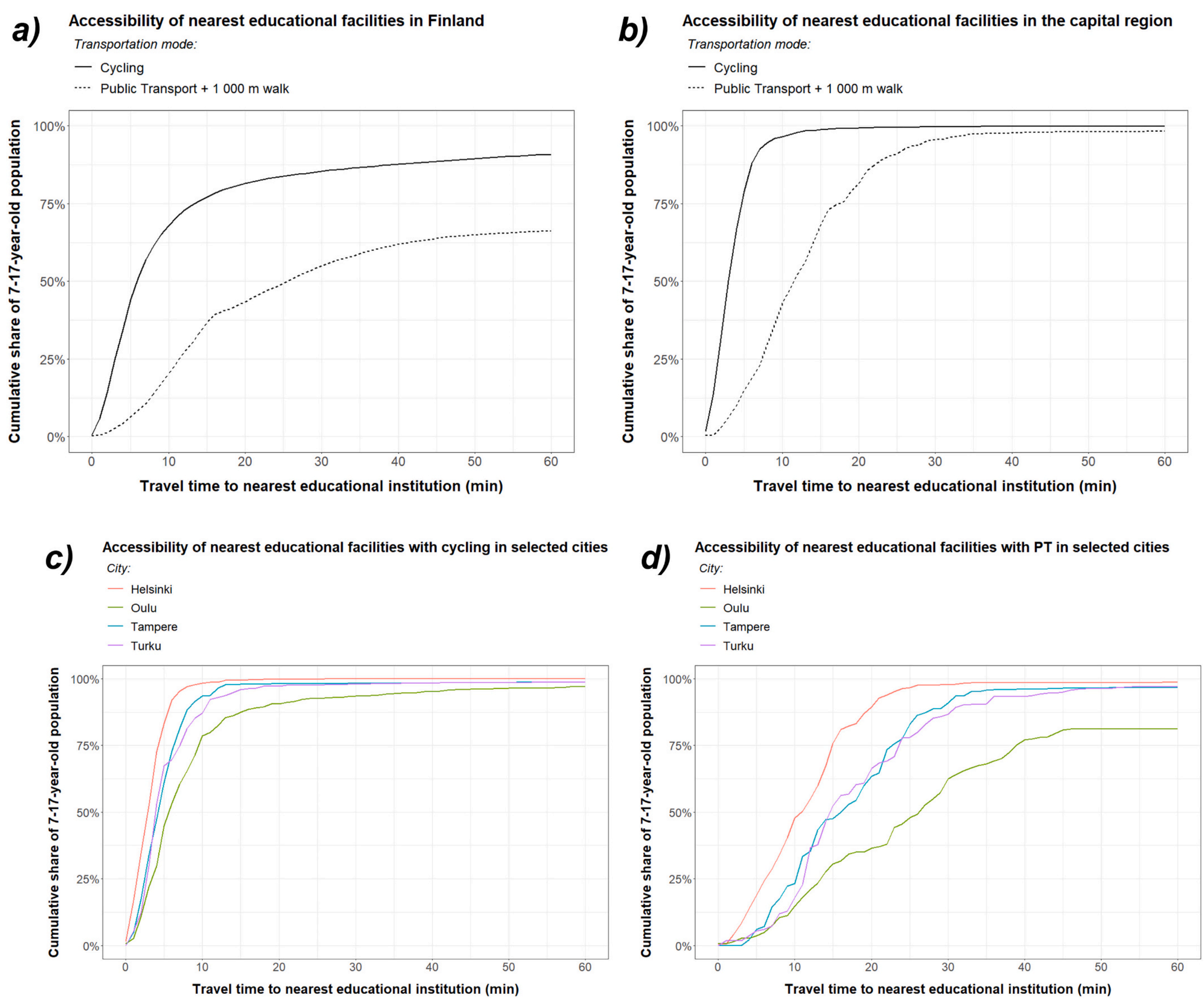

Fig. 6. Travel time comparisons to nearest educational institutions with different modes in relation to cumulative share of the 7–17-year-old population a) in Finland, and b) in the capital region of Finland. Graphs at the bottom compare access to nearest educational institutions across the largest cities in Finland by c) cycling and d) public transport.

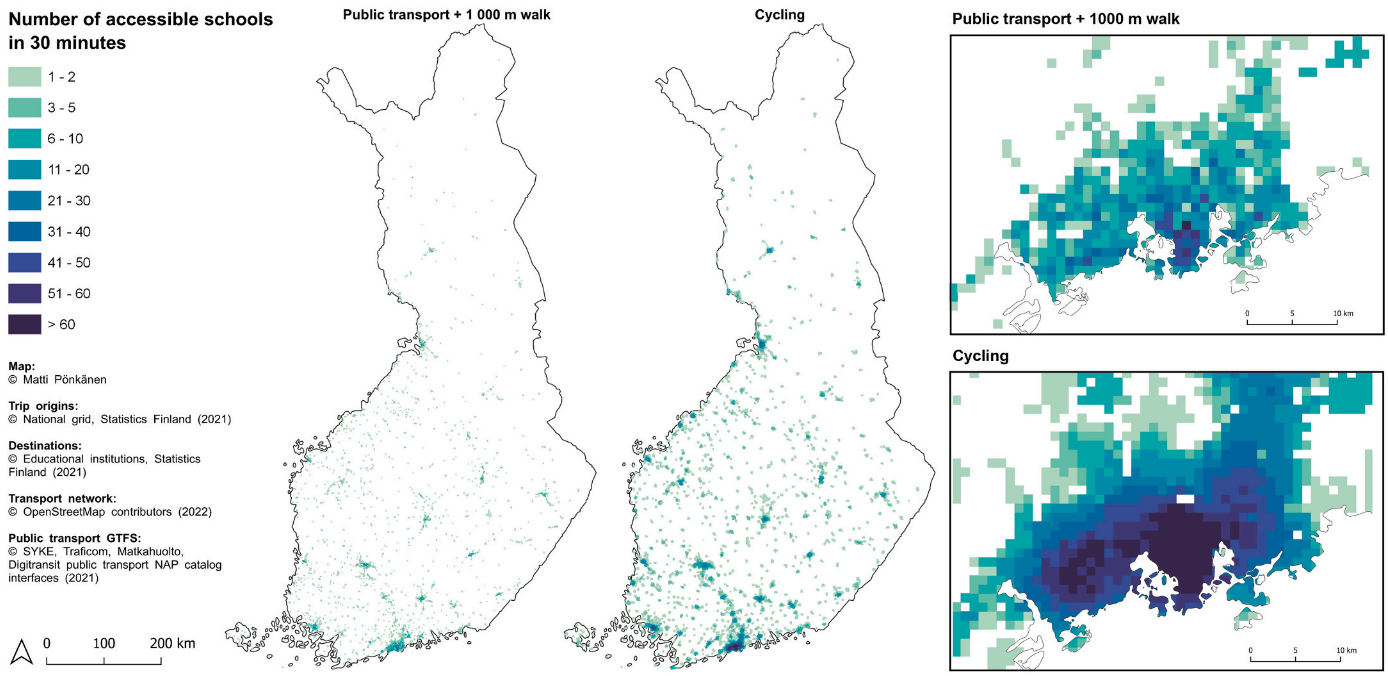

Fig. 7. Spatial distribution of cumulative access to educational facilities.

only 25 % of the total population can do the same with public transport. However, it is important to note, that public transport access in the data covers only specific time slots during a day (7:00–7:30 am departure time for education and workplaces and 10:00–10:30 am for other opportunity types) so there are also temporal variations to account for.

4.2. The equity of access in Finland to different opportunities

Figs. 8 and 9 show the distribution of access in Finland to selected opportunities based on Palma-ratio which can be used as a generalized inequality score to compare access differences between different incomes in different municipalities. Fig. 8 shows the results based on public transport with a 60-min maximum travel time threshold, whereas Fig. 9 does the same but by cycling with a 30-min threshold,

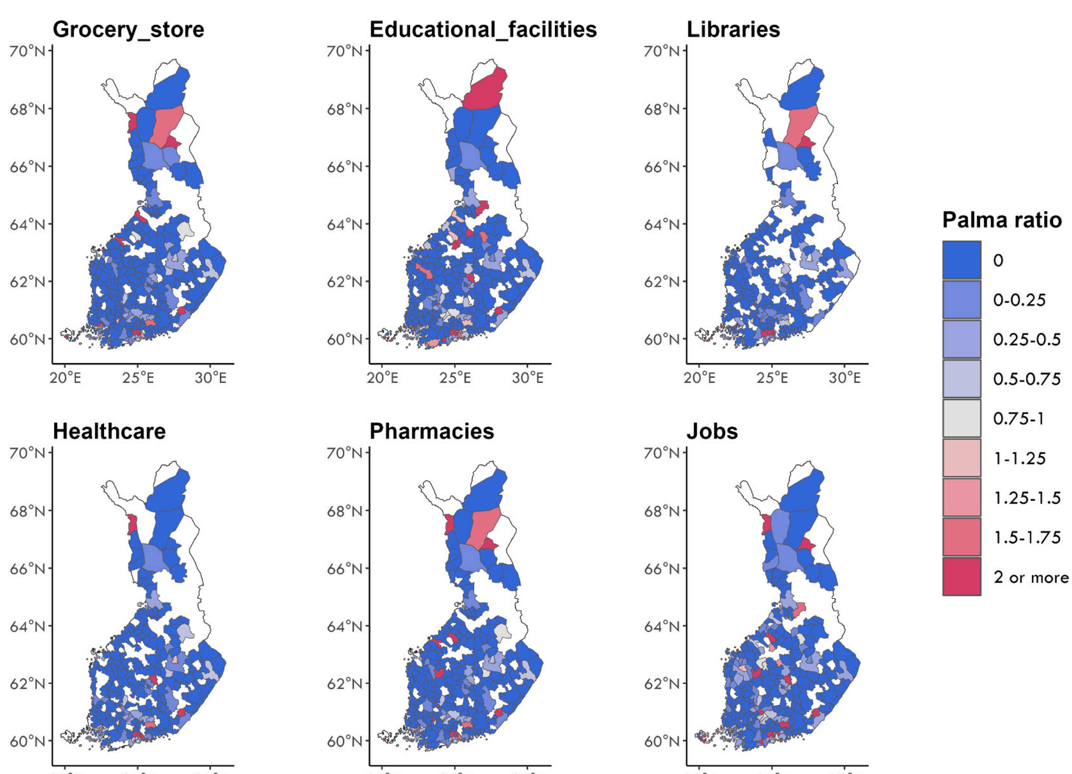

Fig. 8. Palma ratios for different opportunity types calculated for all Finnish municipalities based on public transport using 60 min maximum travel time threshold.

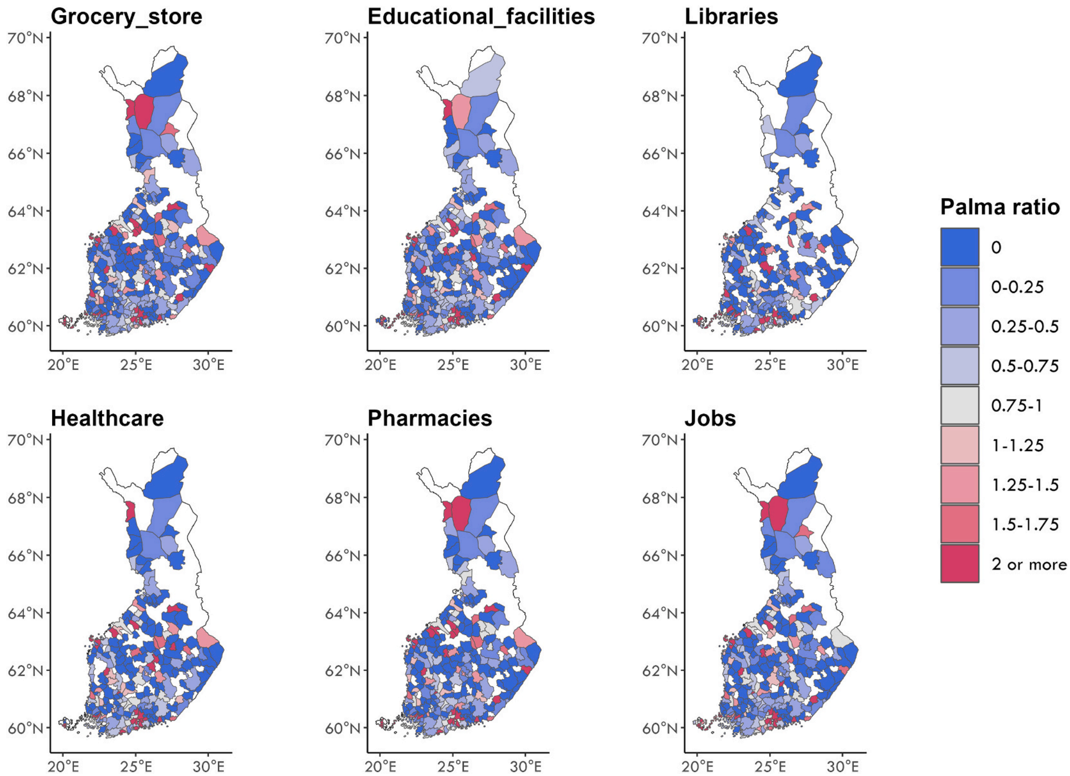

Fig. 9. Palma ratios for different opportunity types calculated for all Finnish municipalities based on cycling using 30 min maximum travel time threshold.

respectively. Our results show that the largest disparities are typically located in municipalities surrounding large city regions, where the Palma ratio is often higher than 2 for most opportunities. This is an interesting finding which reflects the urban development around the large cities in Finland in the past decades, where wealthier people (often with a job in the city) have moved out to the neighboring municipalities, possibly due to more living space and better life conditions. Some municipalities close to the city of Helsinki are examples of such places, where the wealthiest residents tend to have better access to various opportunities compared to the poorest 40 % of the inhabitants, both based on cycling as well as public transport. On the contrary, the large cities themselves (e.g. the cities of Helsinki, Tampere, Turku and Oulu) typically have a Palma ratio close to 1 indicating that the access to opportunities is equal regardless of the income (also see Table 3). Large cities typically have a denser network of services and opportunities distributed around the city, which is the likely reason for good and equal access.

Table 3 shows the Palma ratios for the ten largest cities in Finland (ordered by population) based on maximum travel time of 45 min by cycling and public transport. These cities cover approximately 42.5 % of Finnish population (2.38 million inhabitants). The results show that out of these cities, the most equitable municipality in terms of access to opportunities is the third largest city in Finland, Tampere. For cycling, all Palma ratio values are very close 1.0, i.e. access is equal regardless of the income. Also, for the public transport the Palma ratios in Tampere are not far from equilibrium, and in most cases, the bottom 40 % income group has slightly better accessibility to the opportunities compared to the top income decile. Finland's capital Helsinki also provides very equitable access to opportunities, and based on public transport it is the most equitable of the selected cities with values close to 1 for majority of the opportunities. However, healthcare accessibility in Helsinki is better for the top income decile by both travel modes, as well as job accessibility by cycling. The City of Espoo (2nd largest city) has the highest number of opportunity types in which the accessibility (by cycling) is better for the top income group (libraries, jobs, healthcare and pharmacies). Interestingly, the situation is quite the opposite when traveling is done by public transport, as most of the values indicate better access for the bottom income group. This happens most likely due to

Table 3
Palma ratios for different opportunities listed for the largest Finnish municipalities (ranked by population) using 45-min maximum travel time by cycling and public transport. Values with ***bold cursive text*** highlights Palma ratios above 1.2 indicating better access for the top income group, while Palma ratios below 0.8 are highlighted with bold text indicating better access for the bottom income group. The values without highlight indicate that the access is close to equilibrium.

	Cycling – 45 min threshold							Public transport – 45 min threshold						
Municipality	Grocery	Edu	Library	Jobs	Health	Pharm.	Sports	Grocery	Edu	Library	Jobs	Health	Pharm.	Sports
1. Helsinki	1.09	0.99	1.05	***1.37***	***1.68***	1.06	0.90	1.01	0.96	0.94	1.19	***1.40***	1.02	0.89
2. Espoo	1.12	1.02	***1.28***	***1.37***	***1.26***	***1.30***	1.05	**0.75**	**0.62**	**0.86**	**0.66**	0.90	0.80	**0.66**
3. Tampere	1.02	1.00	1.04	0.99	1.11	1.03	1.10	0.87	0.84	**0.78**	0.87	1.05	0.89	0.99
4. Vantaa	**0.74**	0.82	**0.67**	1.01	0.94	**0.73**	0.93	**0.33**	**0.41**	**0.27**	**0.49**	**0.59**	**0.35**	**0.41**
5. Oulu	**0.74**	**0.78**	**0.74**	**0.76**	0.89	0.82	0.85	**0.29**	**0.37**	**0.18**	**0.40**	**0.42**	**0.34**	**0.27**
6. Turku	**0.66**	**0.56**	**0.65**	**0.64**	**0.69**	**0.63**	**0.48**	**0.18**	**0.23**	**0.12**	**0.22**	**0.17**	**0.15**	**0.17**
7. Jyväskylä	**0.64**	**0.62**	**0.64**	**0.63**	**0.69**	**0.63**	**0.65**	**0.18**	**0.26**	**0.29**	**0.29**	**0.21**	**0.21**	**0.21**
8. Kuopio	**0.72**	**0.76**	**0.73**	**0.61**	**0.42**	**0.72**	**0.65**	**0.47**	**0.36**	**0.26**	**0.37**	**0.11**	**0.52**	**0.34**
9. Lahti	0.91	0.86	**0.75**	0.89	0.84	0.93	0.85	**0.43**	**0.53**	**0.35**	**0.48**	**0.49**	**0.49**	**0.38**
10. Pori	**0.26**	**0.22**	**0.28**	**0.22**	**0.19**	**0.26**	**0.29**	**0.05**	**0.01**	**0.08**	**0.00**	**0.00**	**0.04**	**0.10**

centralized spatial distribution of the opportunities, and at the same time, the public transport service level is better in areas where lower income people live, and/or people belonging to the top income decile tend to live in more remote areas of the city. Finally, the results reveal that in most of the selected cities the access to opportunities tends to be better for the bottom 40 % income group as majority of the Palma ratios are clearly below 1, both by cycling as well as public transport.

5. Discussion and conclusions

5.1. Importance and usability of accessibility information in Finnish planning practice

In the following, we share the insights from the transport planning practitioners that demonstrate how the accessibility information can provide value for transport policy and planning (in the paragraphs starting with "Practitioners' perspective"), followed by a reflection on these perspectives from our perspective.

Practitioners' perspective: The planners stated that the general importance of accessibility in planning practice has witnessed development since the early 2000s, aligning with international trends. This evolution includes technical advancements, such as opening of GTFS data, even though the use of open source tools is still largely missing. Thus, evaluating accessibility is considered important as it helps to move away from just measuring travel time of private car driving, and putting more emphasis on supporting walking, cycling, and public transport for climate and health public policy goals. Besides these impacts, accessibility plays a crucial role in preventing segregation. Although equity as a concept is recognized as important due to its relation to equality and other notions of the Nordic welfare state, the specific notion of equity based on distributive justice principle is not yet completely understood and discussed enough in practice. Planners also underlined that while politicians frequently use the term accessibility, its definition and implications remain undefined, potentially leading to misunderstandings, such as equating it with the focus on economic growth. Moreover, recent reforms in the healthcare and social sector have substantially affected accessibility across Finland. Besides the access to health services, accessibility to daycare centers and schools was also highlighted as important.

As was highlighted by the practitioners, there are a few fundamental aspects worth noting related to the use of accessibility indicators and various mobility parameters. No matter if we are constructing an accessibility dataset to measure the sufficiency of access or the disparities in access, when operationalizing a metric that does this, there are always underlying assumptions that are made about the population that is being analyzed. By setting different mobility attributes into models (e.g., walking and cycling speed, available transport modes, number of transfers) and selecting different opportunities (e.g., healthcare, education, etc.) for the analysis, we are already casting a normative assumption on how the population groups investigate are moving through space, how they want to access places, and what kind of opportunities they need access to. Thus, these building blocks of the analysis are already impacting the boundaries of what can be considered as accessible within the produced measures. Different population groups might also have significant differences in their tolerance for different levels of access (van der Veen et al., 2020). As Páez et al. (2012) have argued, ultimately what is determined to be a sufficient level of access should be decided through a normative process, instead of a positivist one. A similar conclusion can be made about the process of setting attributes that impact mobility characteristics inside models. To decrease arbitrariness of values in planning processes, the selection of thresholds should be as transparent as possible and optimally decided through collective decision making.

5.2. Usefulness of the online tool and the accessibility indicators

Practitioners' perspective: The planners highlighted that the presented maps and graphs already serve as versatile tools with diverse applications in planning, playing a pivotal role as conversation starters and providing essential baseline information. Their widespread use is particularly crucial given the limited capacity of municipalities and regions to create such infographics. Notably, sectors beyond transport and land use, such as healthcare planning, may not fully leverage this kind of information. The tool's applicability extends to communicative planning across different disciplines and roles, including residents and politicians, recognizing the inherent political dimension in planning that data alone cannot erase. The infographics prove valuable in various planning and policy processes, such as determining public transport fare schemes and subsidies, as well as rail-based infrastructure planning. Their utility also extends to ex-ante evaluation (e.g. in MAL agreements), helping to identify problem hotspots and facilitating decision-making by revealing underperforming municipalities. Additionally, infographics can help in monitoring agreements and improving the definition of desired targets, such as setting specific percentages for children walking to school within a defined distance. Moreover, they enable the development of ranking lists and relative comparisons under budget constraints, complementing traditional travel demand modeling, although maps depicting spatial distribution of opportunities are underutilized in practice. Furthermore, the use of the tool and maps enhances understanding the limits and trustworthiness of the data, thus guiding priorities for data collection. Finally, the usability of the tool lies in its effectiveness for visual-analytical communication in one view, offering interactivity through browser solutions, in contrast to passive presentation methods, such as PowerPoint slides.

As our discussions with Finnish planners reveal, providing an easy-to-use tool to communicate national-level accessibility information is highly valuable for various planning and policy processes, which is also in line with recent studies focusing on equity assessments (LeClair et al., 2023). Comparable national level accessibility analyses and associated tool as presented in this paper, can provide common starting point for evaluating the levels of access in different parts of Finland and provides a way to discuss about the situation in different municipalities.

5.3. Limitations and future development directions

Practitioners' perspective: One aspect that the planners pointed out was that the visualizations and indicators in planning are needed in various spatial and temporal scales, ranging from national, regional to municipal and neighborhood levels. The spatial scale includes administrative regions, as well as finer scales like grids, postal codes, and customized districts, while the temporal scale ranges from considerations for morning peak periods up to changes over several decades. Thus, being able to integrate various spatial-temporal scales to the tool would be useful. Challenges also arise among planners in understanding the Palma ratio and utilizing the income as a differentiation factor. Moreover, regarding the tool's usefulness, the significance of everyday mobility destinations, such as healthcare and primary prevention centers over hospitals, was emphasized by the planners. Finally, planners also suggested adding an import function, allowing the addition of specific points of interest, as this functionality would enhance the planning process that often includes unforeseen additions in impact assessment.

As demonstrated by our discussions with the stakeholders, the presented data and the tool in its current form are useful but not yet sufficient for every planning application. The tool should provide possibilities to evaluate access at different spatial scales, as well as consider the temporal dimension that allows inspecting the changes in access over multiple years (e.g. Tenkanen & Toivonen, 2020). Indeed, our analysis is rather atemporal by nature, and one of the limitations is the rather coarse spatial resolution of the analysis (1 × 1 km) which might not reveal the more nuanced disparities in access within urban areas that might be visible only at higher spatial resolution. This Modifiable Area Unit Problem (MAUP) is a well-known issue in geography (Fotheringham & Wong, 1991; Openshaw, 1984) that can influence on the interpretation of the results and limit the possibilities e.g. for guiding policy recommendations at city-region level. However, we believe that for national-level analysis this resolution provides useful input.

Scaling the input data up to national levels also increases the risk of data inaccuracy, thus requiring careful data validation. One of the most challenging tasks related to accessibility analyses is to coordinate a national GTFS dataset used for public transport modeling (here validated by Finnish Environment Institute), and gathering up-to-date and consistent a destination choice set. For example, the number of grocery stores in OpenStreetMap significantly differs from the dataset that we gathered from the actual store websites for our analyses. Therefore, if possible, it is best to use data verified by officials or obtained directly from an organization that provides the actual service.

The decision to rely on specific travel cost impedance also introduce uncertainty in the results. Choosing a specific impedance can impact analytical results and thus impact policy decisions that are based on results. The limitations that were set by the national context in this study made it difficult to operationalize a utility or space-time-based measure because of their individual-level data requirements, although they could provide more nuanced results across all different spatial contexts. Cumulative measures have typically lower data requirements, making them more easily scalable for national level to explore potential causes for subpar accessibility. In future studies gravity-based measures could be explored and compared as an alternative measure.

The *R5* and *r5r* also do have some limitations. One limitation is that using custom networks requires advanced knowledge of tools, such as JOSM (Java OpenStreetMap editor) which can be challenging, especially in national contexts. Otherwise, the user must rely on OpenStreetMap data that can have some data deficiencies in more sparsely populated areas, although some might consider the use of OpenStreetMap data as a benefit as it makes the results more universal. Another limitation that we found is that the user cannot control the distance, how far origin and destination points are snapped to the transport network in r5r. Instead, the maximum snapping distance is defaulted as 1.6 km. This can be a disadvantage for some scenarios, where smaller grid size is used, and the network tends to be sparse. In situations in which the user wants to use shorter snapping distances, a manual customization of origins and destinations is needed. Alternatively, the *r5py* Python wrapper for *R5*, allows specifying custom snapping distance as a parameter directly in the tool (Fink et al., 2022).

5.4. The potential of accessibility tools for future planning practice

Practitioners' perspective: The asynchronous use of tools in planning proves invaluable, especially considering the limited time available for interaction between planners and politicians. These tools facilitate learning as they can aid politicians in understanding the broader scope of planning beyond simply securing national government funding for specific infrastructure projects. Moreover, tools contribute to the continuity of institutional memory, enhancing preparation and discussions during steering groups involving experts from various stakeholder organizations. Importantly, these tools contribute to improving expertise among civil servants, emphasizing the need for in-house knowledge beyond reliance on external consultants. On the one hand, vertical integration is addressed by clarifying the roles of national agencies in relation to municipalities, especially within the emerging national transport planning process. This would help with preventing oversight due to a municipal focus on land use benefits and avoid the risk of top-down planning that prioritizes regional accessibility over the needs of individuals. On the other hand, horizontal integration efforts are observed as regular communication among different Finnish ministries. Further integration across sectors, especially healthcare and social services, is highlighted as crucial for efficient use of public funds, necessitating structured processes and events for discussions. Some services that are mandatory for municipalities, particularly in traffic safety and school-related aspects, are emphasized in the context of human-scale planning paradigm, exemplified by initiatives such as service network planning, which now incorporates analysis of specific resident groups. Finally, the need for innovation in governance is recognized, particularly in delineating roles and responsibilities at the national level. This extends to monitoring regional development and negotiations with regions, where these tools can empower regions to raise concerns with a specific ministry.

Indeed, as reflected by the practitioners, computing accessibility measures especially for large areas are often associated with tedious and time-consuming workflows (Pereira et al., 2021). To resolve this issue, the number of locations analyzed is usually reduced, or analysis is simplified drastically e.g. by using simple buffers as a radius of access. However, advances in open source tools and parallel computing, as demonstrated in this study, have made accessibility modeling far more efficient. Using r5r can lead to calculations 6 to 200 times faster compared to commercial alternatives, such as ArcGIS Pro or Emme (Higgins et al., 2022), making it a capable tool for national scale analysis. Calculating a travel time matrix for the whole nation took 18 min for cycling and 55 min for public transport, while running cumulative metrics for all grocery stores across the nation, took 40–44 min depending on the mode (see Supplement S1 for further details). With the increased processing power and more efficient computational tools, producing accessibility metrics using actual transport networks has become less cumbersome, allowing planners and researchers to tackle even larger datasets within typical workflows. For example, a planner could automate multiple different accessibility scenarios to be run during meetings for the whole nation. When you couple these results with population statistics, planners can easily explore the differences in access across populations.

The functionality of these open source tools has also expanded to new levels and allows the user to explore new research pathways. For example, with the r5r library it is possible to examine multiple different travel-time cut-offs, opportunities and construct various mobility profiles for the analysis by setting individual mobility parameters (as shown in Table 2). This can be highly useful for planning practice, as planners can use these parameters to construct different mobility profiles easily and quickly, and e.g. consider different levels of travel comfort for cyclists. These advances enable a new level of equity-based analyses in which scenario datasets are produced in a disaggregated manner for different population groups.

Open source tools make it also possible to conduct democratically accountable transport planning workflows (Lovelace, 2021) by opening the various assumptions and modeling-related decisions that have been made related to a specific analysis. Open software also reduces arbitrary results by supporting transparent community driven processes in transport planning that can lead to more democratic decision making. Open source tools are typically also more flexible when compared to their closed-sourced counterparts, and they can evolve and expand quickly as a community effort. For instance, it did not take long for a Python wrapper (*r5py*) for the R5 routing engine to emerge after the r5r wrapper was released (Fink et al., 2022). Planners and decision makers can also modify these tools to their own specific problem frameworks, that can be used for constructing analyses for evidence-based decision making and scientific research. Other significant benefits include the reduced costs. No longer does a planner or researcher necessarily require expensive software licenses when there are free options available. In some cases, these open source alternatives can perform the job better than their closed-sourced counterparts as demonstrated by Higgins et al. (2022).

CRediT authorship contribution statement

Matti Pönkänen: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization, Writing – review & editing. **Henrikki Tenkanen:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Software, Project administration, Methodology, Investigation, Data curation, Conceptualization, Formal analysis. **Miloš Mladenović:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.compenvurbsys.2024.102218.

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