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User-specific walking accessibility

Addressing the mismatch between calculated and perceived walking accessibility measures

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“Diversity is about all of us, and about us having to figure out how to walk through this world together.”

(Jacqueline Woodson)

Preface

I come from a small town in the south of Germany with 18,000 inhabitants, actually a perfect 15-minute city. From my parents' house, all daily needs are accessible within 10 minutes walking. From any place in the town, you can easily reach any other place within 15 minutes by bike. Thus, my daily childhood routine was shaped by this: walking 12 minutes to school or, if I was a bit late, taking the bicycle, which only took me 5 minutes. In my free time, I was meeting my friends, who mostly also lived within a 5-minute bike ride, or went to the city centre; a historic pedestrian zone. My parents only very rarely drove me anywhere by car. Thus, I was very much used to walking and cycling and I must say I loved it (and still do!).

Ever since the first of my friends turned 18, I was asked every time we met in town if they should pick me up. My answer has always been “no” (only in awful weather conditions, I tend to say “yes”). Because 1) I see no point in driving. By car, it takes 3 minutes to reach the city centre, 5 minutes to find a parking lot and another 5 minutes to walk from the parking lot to where we want to go. Thus, it takes me longer than walking directly from home. 2) I enjoy walking. Before sitting in a bar for glasses of wine, it's really nice to have at least a bit of physical movement. 3) It clears my mind. No matter what I have done before, this 10-minute walk allows me to calm down and mentally prepare myself for the person(s) I am about to meet. 4) One route leads along the river Rhine, which is just super beautiful and relaxing, especially when compared to driving on the congested main road.

But – as you can probably guess from the fact that after more than ten years of saying “no”, I am still asked if I want to be picked up by car – none of my friends understand why I prefer walking over driving. Each of them has their own reason not to walk. One lives uphill and would need to invest exhausting minutes on the way back home. Another would have to walk through a park where male teenagers regularly hang out, and she is afraid to pass them, especially at night. Two others live a bit further towards the outskirts and would need 15-20 minutes of walking, which they consider too long. These were mainly the reasons ten years ago but are still comparable today.

Why am I telling this story? I have a passion for walking and believe it's a great means of transport that more people should use for their everyday trips! Therefore, appropriate walking conditions are essential. While I know that I cannot change the world, I hope to gain at least some insights that will help others plan pedestrian-friendly cities that meet everyone's needs.

Abstract

Climate change is one of the main challenges humanity currently faces. To mitigate its severity, the transport sector needs to reduce greenhouse gas emissions. Walking is essential to make the transport sector more sustainable, as it can be considered the most sustainable means of transport. In addition, walking is not only a means of transport itself; it is also needed to start and end a trip with any vehicle and is an essential enabler of public transport and shared mobility. To encourage people to walk, their walking needs must be fulfilled. This includes walking accessibility through nearby destinations and a walkable infrastructure in terms of security, safety, comfort, and pleasurability that meets the needs of all.

Accessibility instruments are valuable tools for decision support, but for walking, a general mismatch between calculated and perceived accessibility has been identified. The reason for this is the neglect of the perceptions of different user groups and the isolated assessment of accessibility, with the disregard of walkability elements. This mismatch shows that existing measures are unable to model walking accessibility adequately. With the aim of reducing the mismatch between perceived and calculated walking accessibility, this dissertation develops a transferable measure for modelling perceived walking accessibility that can be tailored to specific user groups. Therefore, three research questions arise: “Which walking accessibility studies exist, what do they consider and what are they missing?”, “Which attributes have an impact on perceived walking accessibility?” and “How can the variety of perceptions be represented in feasible, calculated accessibility measures?”.

In order to answer these questions, first, a literature review on existing accessibility measures was carried out, and recommendations for future measures were drawn. Second, a survey on perceived accessibility was conducted and compared with calculated accessibility to explore the mismatch further. Moreover, the survey results were statistically analysed to better understand the factors that influence perceived accessibility. Finally, a Perceived user-specific Accessibility measure for Walking (PAW) was developed and applied in a case study. The Analytic Hierarchy Process (AHP) method was used to determine the weights of different influencing factors for four sample user groups (seniors, children, wheelchair users, women).

Findings indicated that conventional calculated accessibility measures do not do justice to the four accessibility components defined by Geurs and van Wee (2004); in particular, the individual and temporal components are neglected. Furthermore, they usually do not represent the pedestrian network with all its micro-elements. Impedance is typically determined by distance or time, whereas perceived walking time is more accurate. By comparing the survey results with the calculated accessibility, the mismatch between perceived and calculated accessibility measures was confirmed, highlighting the inability of conventional calculated accessibility measures to capture the accessibility as it is perceived by people. Perceived accessibility was found to be influenced by many factors: accessibility, walkability, user characteristics, geographical context and temporal changes. Following the findings, the measure PAW was developed. PAW uses imputed perceptions, which are presented as the key to closing the gap between perceived and measured accessibility. Therewith, the perceived walking times can be inferred by evaluating how well the walking infrastructure meets the user's needs. The results show that conventional accessibility measures often overestimate, but sometimes also underestimate, accessibility compared to PAW.

However, it has not yet been proven that PAW represents walking accessibility more realistically than existing measures. PAW fulfils many of the drawn recommendations, but some decisions in the development process were made in favour of simplicity instead of accuracy. The measure focuses on modelling the individual component and its interplay with the transport component; thereby, the temporal component is excluded, and the land-use component is only considered partially. The factors influencing perceived walking accessibility are understood better but cannot be considered conclusive, as the interdependencies are complex. Four user groups have been studied in the development of PAW. However, these are only examples. PAW can be adapted to any user group and transferred to study areas worldwide. But it should be noted that the measure results can only be as good as the input data.

This research has contributed to the overall understanding of walking accessibility and can help to increase the awareness of walking needs and apply these findings to planning practice. The gap between perceived and calculated accessibility measures has not been completely closed, but presumably narrowed.

Zusammenfassung

Der Klimawandel ist eine der größten Herausforderungen, vor denen die Menschheit derzeit steht. Um das Ausmaß des Klimawandels einzudämmen, muss der Verkehrssektor die Treibhausgasemissionen reduzieren. Das Zufußgehen ist für eine nachhaltigere Ausrichtung des Verkehrssektors unerlässlich, da es als das nachhaltigste Verkehrsmittel angesehen werden kann. Außerdem beginnt und endet jeder Weg, unabhängig von der Art des Verkehrsmittels, zu Fuß. Das Zufußgehen ist daher ein wichtiger Bestandteil des öffentlichen Verkehrs und der Shared Mobility. Um zu erreichen, dass mehr Menschen zu Fuß gehen, müssen ihre Gehbedürfnisse erfüllt werden. Dies bedeutet eine gute fußläufige Erreichbarkeit zu Zielen des täglichen Bedarfs und eine attraktive Fußverkehrsinfrastruktur in Bezug auf soziale Sicherheit, Verkehrssicherheit, Komfort und Genuss, die den Bedürfnissen aller gerecht wird.

Erreichbarkeitsinstrumente sind wertvolle Entscheidungshilfen. Für den Fußverkehr wurde jedoch eine allgemeine Diskrepanz zwischen den Ergebnissen berechneter und wahrgenommener Erreichbarkeitsanalysen festgestellt. Grund dafür ist die Vernachlässigung der Wahrnehmung verschiedener Nutzer:innengruppen und die isolierte Bewertung der Erreichbarkeit ohne Berücksichtigung von Walkability-Elementen. Diese Diskrepanz zeigt, dass bestehende Erreichbarkeitsindikatoren nicht in der Lage sind, die fußläufige Erreichbarkeit adäquat abzubilden. Mit dem Ziel, die Diskrepanz zwischen wahrgenommener und berechneter fußläufiger Erreichbarkeit zu verringern, wird in dieser Dissertation ein übertragbarer Indikator zur Modellierung der wahrgenommenen fußläufigen Erreichbarkeit entwickelt, der für unterschiedliche Nutzer:innengruppen kalibriert werden kann. Dazu werden drei Forschungsfragen gestellt: „Welche Studien zur fußläufigen Erreichbarkeit existieren, was wird berücksichtigt und was vernachlässigt?“, „Welche Attribute beeinflussen die wahrgenommene fußläufige Erreichbarkeit?“ und „Wie kann die Vielfalt der Wahrnehmungen in praktikablen, berechneten Erreichbarkeitsindikatoren abgebildet werden?“.

Zur Beantwortung dieser Fragen wurde zunächst eine Literaturrecherche zu existierenden Erreichbarkeitsindikatoren erstellt und Empfehlungen für zukünftige Indikatoren abgeleitet. Zweitens wurde eine Umfrage zur wahrgenommenen Erreichbarkeit durchgeführt und mit der berechneten Erreichbarkeit verglichen, um die Ursachen der Diskrepanz besser zu verstehen. Darüber hinaus wurden die Umfrageergebnisse statistisch ausgewertet, um die Einflussfaktoren der wahrgenommenen Erreichbarkeit zu analysieren. Schließlich wurde ein nutzergruppenspezifischer Indikator für die wahrgenommene fußläufige Erreichbarkeit „PAW“ (Perceived user-specific Accessibility measure for Walking) entwickelt und in einer Fallstudie

angewendet. Mit Hilfe der AHP-Methode (Analytic Hierarchy Process) wurde die Gewichtung der verschiedenen Einflussfaktoren für vier exemplarische Nutzer:innengruppen (Senior:innen, Kinder, Rollstuhlfahrer:innen, Frauen) ermittelt.

Die Ergebnisse zeigen, dass herkömmliche berechnete Erreichbarkeitsindikatoren den vier Erreichbarkeitskomponenten, definiert durch Geurs und van Wee (2004), nicht gerecht werden; insbesondere die individuelle und die zeitliche Komponente werden vernachlässigt. Außerdem bilden sie meist nicht das Fußwegenetz mit allen zugehörigen Mikroelementen ab. Die Widerstandsfunktion wird in der Regel durch die Distanz oder die Zeit bestimmt, während die wahrgenommene Gehzeit die genauere Methodik wäre. Der Vergleich der Befragungsergebnisse mit den berechneten Erreichbarkeiten bestätigt die Diskrepanz zwischen der wahrgenommenen und der berechneten Erreichbarkeit. Dies macht deutlich, dass die herkömmlichen berechneten Indikatoren nicht in der Lage sind, die Erreichbarkeit so zu erfassen, wie sie von den Menschen wahrgenommen wird. Die wahrgenommene Erreichbarkeit wird von vielen Faktoren beeinflusst: Erreichbarkeit, Walkability, Charakteristika der Nutzer:innen, geografischer Kontext und zeitliche Veränderungen. Basierend auf diesen Erkenntnissen wurde der Indikator PAW entwickelt. PAW basiert auf zugeschriebenen Wahrnehmungen, die als Schlüsselelement zur Schließung der Lücke zwischen wahrgenommener und gemessener Erreichbarkeit angesehen werden. Damit können wahrgenommene Gehzeiten abgeleitet werden, indem bewertet wird, wie gut die Gehinfrastruktur den Bedürfnissen der Nutzer:innen entspricht. Die Ergebnisse zeigen, dass herkömmliche Indikatoren die Erreichbarkeit im Vergleich zu PAW oft überschätzen, manchmal aber auch unterschätzen.

Allerdings wurde bisher noch nicht bewiesen, dass PAW die fußläufige Erreichbarkeit realistischer abbildet als bestehende Indikatoren. PAW erfüllt viele der ausgearbeiteten Empfehlungen, aber bei der Entwicklung wurden einige Entscheidungen zu Gunsten der Einfachheit und nicht der Genauigkeit getroffen. Der Schwerpunkt von PAW liegt auf der Modellierung der individuellen Komponente und ihrer Interaktion mit der Verkehrskomponente, wobei die zeitliche Komponente vernachlässigt und die Flächennutzungskomponente nur teilweise berücksichtigt wird. Das Verständnis der Einflussfaktoren, die für die Wahrnehmung der fußläufigen Erreichbarkeit ausschlaggebend sind, hat sich verbessert, kann aber aufgrund der Komplexität der gegenseitigen Abhängigkeiten nicht als abschließend betrachtet werden. Bei der Entwicklung von PAW wurden vier Nutzer:innengruppen untersucht. Dies sind jedoch nur Beispiele. PAW kann an jede beliebige Nutzer:innengruppe angepasst und auf Untersuchungsgebiete weltweit übertragen werden. Dabei ist jedoch zu beachten, dass die Ergebnisse des Indikators nur so gut sein können wie die Eingangsdaten.

Diese Dissertation hat zum allgemeinen Verständnis der fußläufigen Erreichbarkeit beigetragen und kann das Bewusstsein für die Bedürfnisse von Fußgänger:innen schärfen und helfen, diese Erkenntnisse in der Planungspraxis anzuwenden. Die Diskrepanz zwischen wahrgenommenen und berechneten Erreichbarkeitsindikatoren wurde zwar nicht vollständig beseitigt, aber vermutlich verringert.

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List of abbreviations

A4L	Active for Life
AHP	Analytic Hierarchy Process
AHP-OS	Analytic Hierarchy Process Online System
AI	Artificial Intelligence
ATKIS	Amtliches Topographisch-Kartographisches Informationssystem *(en: Official Topographic-Cartographic Information System)*
BEG	Bayerische Eisenbahngesellschaft mbH *(en: Bavarian railway company)*
CAWS	Capability-Wise Walkability Score
CO_2	Carbon dioxide
DGM ***(en: DTM)***	Digitales Geländemodell *(en: Digital terrain model)*
EAST-HK	Environment in Asia Scan Tool - Hong Kong version
EU	European Union
EX-TRA	EXperimenting with city streets to TRAnsform urban mobility
FGSV	Forschungsgesellschaft für Straßen- und Verkehrswesen e. V. *(en: Research Association for Road and Transport Engineering e. V.)*
GIS	Geographic Information Systems
GOAT	Geo Open Accessibility Tool
IÖR	Leibniz-Institut für ökologische Raumentwicklung (*en: Leibniz Institute of Ecological Urban and Regional Development*)
NDVI	Normalised Difference Vegetation Index
NECTAR	Network on European Communications and Transport Activities Research
NEWS	Neighbourhood Environment Walkability Scale
OSM	OpenStreetMap
OS-WALK-EU	Open-Source Walkability tool for European Union member states
PAW	Perceived user-specific Accessibility measure for Walking
POI	Point-of-Interest
RQ	Research Question
SPACES	Systematic Pedestrian and Cycling Environmental Scan
TUM	Technical University of Munich

US	United States (of America)
WALKIE	Walkability Index
WHO	World Health Organisation

Definitions

This dissertation discusses different elements of accessibility and walkability measures. To maintain consistency throughout the document, the following definitions are used, based on common literature in the field:

Measure: a method to assess a certain concept, e.g. accessibility or walkability.

Indicator: serves to indicate something, e.g. accessibility or walkability. Can be a measure but also more of subjective nature.

Attribute: an element that is taken into account by a measure as an influencing factor.

Score: the result of a measure.

Index: a number expressing the extent of a score.

Analysis: the act of examining something (walkability or accessibility) by using a measure.

When talking about perceptions and users, definitions based on the Oxford English Dictionary are used and partly adjusted to fully match the scope of this dissertation:

User: someone who uses walking as a means of transport.

Need: to require (something) essential or very important (rather than merely desirable).

Ability: the quality in a person which makes an action possible.

Capability: power or ability in general; whether physical or mental.

Preference: a greater liking for one alternative over another or others.

Perception: how something is regarded, understood, experienced or interpreted.

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Part I

Introduction, state-of-the-art, and research design

1. Introduction

1.1. Motivation

Today, in 2024, 8.1 billion people live on our planet. 56% of them in urban areas (United Nations 2022). The world population is growing – especially in cities. By 2050, these numbers are expected to increase to 9.7 billion people in total and 68% of them in urban areas (United Nations 2022). As the population grows, so does the demand for food, housing, jobs, energy and mobility. As a result, the world's cities are growing in size and number. As the overall land size of the planet stays constant, society needs good strategies to use this limited resource wisely. (United Nations 2018)

As a result of the continuing drive for growth, humanity is now facing perhaps its greatest and most urgent challenge: climate change caused by rising greenhouse gas emissions. One of the main emitters is the transport sector. While total carbon dioxide (CO_2) emissions have decreased in the European Union (EU) by 35% since 1990, CO_2 emissions from road transport have increased by 12% in the same period. Around 682 million tonnes of CO_2 were emitted from road transport fuel combustion, accounting for 29% of the CO_2 emissions in 2020. 61% of those were created by cars and motorbikes. (Eurostat 2022)

To mitigate climate change, the transport sector must undergo a transformative shift towards sustainable and low-carbon solutions. This includes not only the widespread adoption of electric vehicles and improvements in public transportation systems, but also the promotion of active transport options such as walking and cycling. Implementing innovations such as electric vehicles presents its own challenges, as it requires the development of extensive infrastructure, the replacement of existing vehicles and the construction of new power plants. This also exacerbates existing challenges, such as increased land consumption and energy demand. While making motorised vehicles more climate-friendly is a valuable endeavour, it is only part of the solution. The urgency of climate change requires more straightforward strategies with fewer negative side effects. Embracing emission-free modes of travel and minimising the distances travelled are crucial steps towards keeping transport-related emissions in check, ultimately helping to curb the effects of climate change on our planet.

One challenge, but also a big opportunity, is that cities are in constant change. Their planning principles react to the current needs of society. While in the 1950s and 60s, the planning of the "automotive city" was considered the right path into a prosperous future, followed by a more sustainable mass transport oriented planning in the 1990s, the current mission statement is the planning of the "15-minute city" (Teixeira et al. 2024). After decades of focusing on motorised vehicles, human-centred cities are now on the rise. The overall motivation is to develop cities that are liveable, also in the long run. A liveable city is characterised by a thriving local economy, the availability of urban green spaces, good accessibility, social justice and a high share of active mobility, i.e. walking and cycling (Tennakoon and Kulatunga 2019).

Walking accounts for 22% of the overall modal split in Germany and even 27% in the metropolitan areas (infas 2018). This is a significant share, which should be further promoted by appropriate measures since walking has many advantages over other means of transport. Walking provides physical and mental health benefits for the general public (Chin et al. 2008; Jou 2011; Lin, Sun, and Li 2015). Walking is simple, social, free, spatially efficient, climate as well as environmentally friendly and promotes the local economy (Jou 2011) and wealth (Florida 2014; Oishi, Koo, and Buttrick 2019). Taking all these advantages into account, walking can be considered the most sustainable means of transport (Jou 2011; Norzalwi and Ismail 2011). However, walking is not only a means of transport itself; walking is also needed to start and end a trip with any vehicle (Boesch 1988). Walking is the main feeder for public transport (Ceder 1998; La Paix and Geurs 2014; Arup 2016) and an essential determinant for the success of shared mobility (Cohen and Shaheen 2018; Roblot et al. 2021).

Despite the high significance of walking, it has not received the deserved attention of transport research and urban planning for a long time (Lo 2009). In recent years, the situation has improved and active mobility is increasingly gaining attention. However, due to the long-standing prioritisation of motor vehicles, an undersupply of walkable environments can still be found in many cities (Leslie et al. 2005).

Every trip starts with a reason, mainly to reach a destination of choice. One of the most prevalent problems that hinder people from walking as main transport mode is the lack of proximity of origins to destinations (Cleland and Walton 2004; Goldsmith 1992), resulting from the disappearance of local activities (Silva and Larsson 2018). The average length of a walking trip in Germany is 2km (infas 2018), meaning that ideally, all destinations for daily needs should be reachable within this distance. However, it is not only nearby destinations that are needed but also suitable footpath networks and an attractive environment. For example, poor walking infrastructure that is not adapted to individual needs (e.g. due to disability) or an environment that creates a sense of danger due to insufficient protection from other traffic flows or poor lighting at night are common problems that discourage people from walking (Cleland and Walton 2004). In general, walking, more than any other means of transportation, depends on the individual capabilities. Worldwide, the share of older persons is increasing. By 2050, 16% of the world’s population will be over the age of 65 (United Nations, Department of Economic and Social Affairs 2022). This highlights the need to plan cities that are inclusive and not just cities that fit the needs of healthy adults. The big challenge is that every city should ideally meet the needs, capabilities and preferences of all its diverse residents of different ages, genders, nationalities and personal characteristics. To fit all, we need to use the most vulnerable as a planning benchmark (Cervero, Guerra, and Al 2017; 8 80 Cities 2023).

In summary, it can be said that especially in times of urbanisation and climate change, focusing on more sustainable modes of transport is inevitable and providing a good walking environment becomes essential for liveable cities (Handy et al. 2002; Langdon 2017). In Germany, 83% of the population states that they enjoy walking, with higher rates of use leading to greater popularity (infas 2018). This shows a huge potential that should be exploited by designing cities that are walkable for everyone, i.e. by providing nearby destinations as well as an appropriate walking infrastructure and environment to achieve a more walking-orientated behaviour of the population (see *Preface*).

1.2. Problem statement and relevance of this work

Walking is essential to making the transport sector more sustainable, not only as a means of transport itself but also as an enabler for other sustainable transport means. Improved walking conditions increase individuals' propensity to walk, resulting in a higher share of walking as a means of transport[1] (Cambra and Moura 2020). To achieve this, two primary needs must be addressed: *walking accessibility* through nearby destinations and *walkability* by providing appropriate infrastructure and an appealing environment. *Accessibility* is defined by Geurs and van Wee (2004) as "the extent to which land-use and transport systems enable (groups of) individuals to reach activities or destinations by means of a (combination of) transport mode(s)", in case of *walking accessibility*, this is limited to the mean of walking. *Walkability* is mainly about how safe, comfortable, and pleasurable the walking paths and their surroundings are perceived by people (American Planning Association 2006; Litman et al. 2009). In order to analyse the current walking conditions, identify shortcomings and subsequently define appropriate actions to improve the situation, models and planning instruments are needed. There are measures for accessibility and walkability, but only a few are trying to analyse both at the same time. Furthermore, many studies found a mismatch between the calculated measure results and the actual perceptions of people (e.g. Curl, Nelson, and Anable 2015; Damurski, Pluta, and Zipser 2020; Gebel et al. 2011; Lättman, Olsson, and Friman 2018; McCormack et al. 2008; Pot, van Wee, and Tillema 2021; Jean Ryan and Pereira 2021; Mark Ryan et al. 2016; van der Vlugt, Curl, and Wittowsky 2019). This leads to an overestimation of

[1] This dissertation focuses on walking as a means of transport. However, if the conditions for walking as a means of transport are attractive, they can also have a positive impact on walking as a leisure activity.

walking conditions and shows that existing measures are unable to adequately model walking accessibility. The reason for this is the neglect of the perception of different user groups. As already Koenig (1980, p. 1) stated, there is a need for user-based accessibility analysis: “Various examples are given, especially for disaggregate analysis where a calculation "for a given person" is proposed instead of the conventional calculation "by a given mode".” To achieve realistic results, accessibility analyses should ideally include walkability elements and user perceptions.

1.3. Research questions and expected outcomes

This research aims to develop a transferable measure for modelling perceived walking accessibility that can be tailored to specific user groups, with the intention of reducing the mismatch between perceived and calculated walking accessibility. The ultimate goal is that this measure will help planners and decision makers in the future to create attractive walking conditions for everyone. Considering that accessibility instruments are valuable tools for decision support (Papa et al. 2015), but for walking, they currently are not able to represent the real, perceived accessibility of people, the overarching goal of this dissertation is to develop a new accessibility measure targeted on walking[2] that includes user needs. More specifically, the research questions of this dissertation are as follows:

RQ 1: *Which walking accessibility studies exist, what do they consider and what are they missing?*

RQ 2: *Which attributes have an impact on perceived walking accessibility?*

RQ 3: *How can the variety of perceptions be represented in feasible, calculated accessibility measures?*

A key component of this approach is the development of a walkability index, which serves to evaluate the attractiveness of pedestrian paths. By translating the attractiveness into perceived time, walkability can be included in accessibility analyses. Furthermore, the accessibility measure can be adjusted per user group. One relevant part of this dissertation is thus also to enhance the understanding of the attributes that influence perceived walking accessibility and how these factors may vary across different user groups. However, the primary goal of this research is not to conclusively evaluate the impact of each individual attribute, as it is virtually impossible to make an exact generalised statement on this, but rather to establish a versatile

[2] For reasons of social justice, the movement by wheelchair or other aids is also considered as walking.

method that can be adapted according to varying input parameters and applied in diverse contexts.

1.4. Structure of the thesis

This dissertation is composed of eight chapters, clustered in three parts. As a paper-based dissertation, Part I (*Chapters 1* to *3*) and Part III (*Chapters 8* and *9*) present the overall framework of this dissertation, while the scientific publications are presented in Part II *(Chapters 4* to *7*).

Chapter 1 presents an introduction to the topic, as well as to the aim and structure of this work. *Chapter 2* reviews the state-of-the-art in accessibility, walkability, user needs and the interplay between them. *Chapter 3* summarizes the research design, including the methodological approach, the research steps, the key methods and the link between the research questions and the scientific publications. The execution and implementation are described in four scientific publications:

Publication 1: *Global interest in walking accessibility: a scoping review*

Publication 2: *Connecting people and places: Analysis of perceived pedestrian accessibility to railway stations by Bavarian case studies*

Publication 3: *Analysis of the quality of footpaths to schools: Development of indicators based on OpenData*

Publication 4: *How does pedestrian accessibility vary for different people? Development of a Perceived user-specific Accessibility measure for Walking (PAW)*

Chapter 8 presents a synthesis and discussion of the findings and is structured by the research questions. *Chapter 9* concludes on the achievements of this work, indicates the limitations and presents an outlook of potential next steps.

The structure of the document is visualised in *Figure 1*, showing the three parts in which the above-mentioned chapters are organised. The different shades of blue indicate how the publications and sections are linked to the research questions.

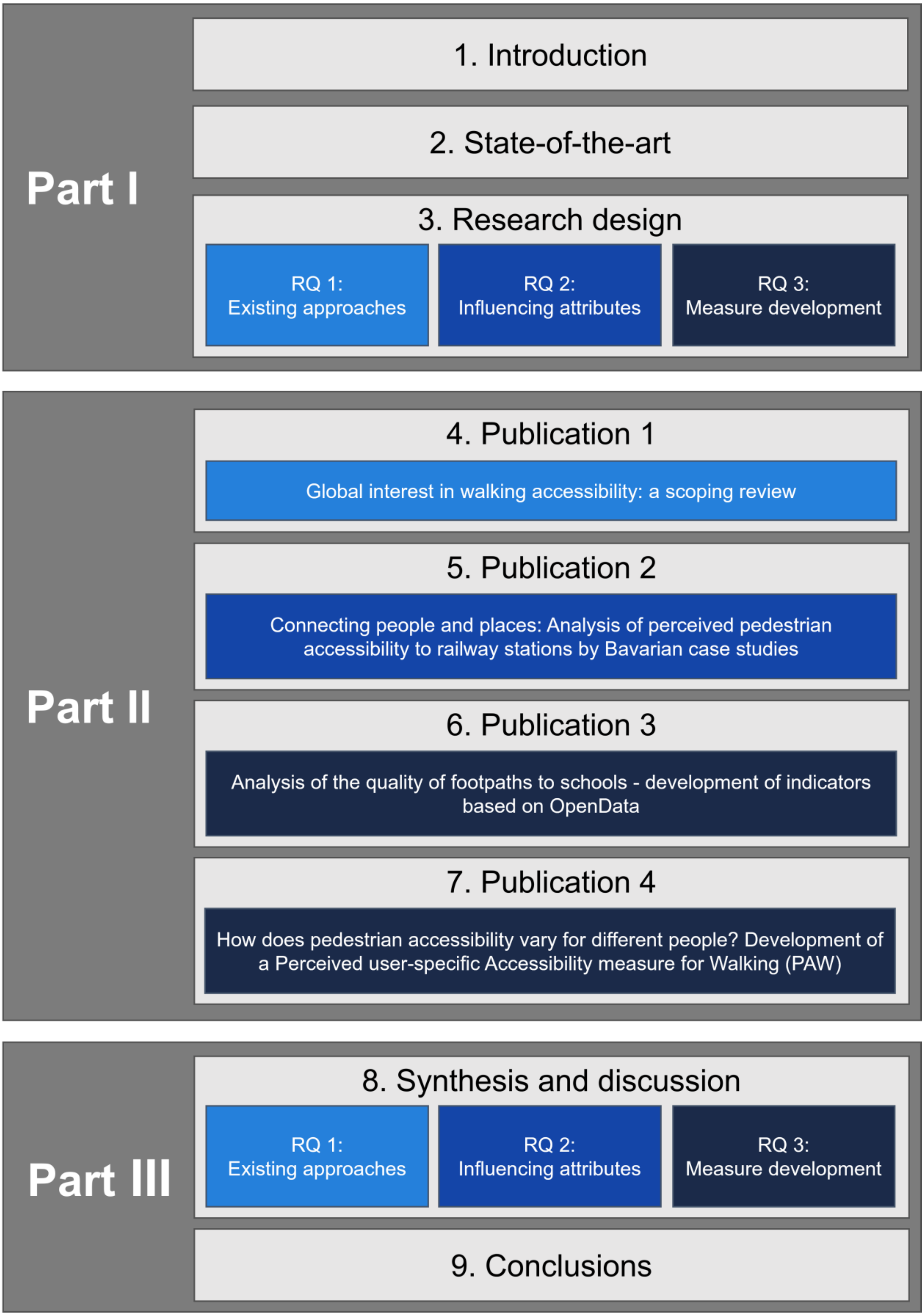


Figure 1: Thesis structure

2. State-of-the-art

2.1. Importance of walking

Promoting walking is an important pillar in making our transport system more sustainable. As walking is considered to be the most sustainable means of transport, it has numerous positive effects on each of the three dimensions of sustainable development (social, economic, environmental).

2.1.1. Social benefits

Walking is the easiest and most affordable form of moving (Southworth 2005), available to almost everyone, independent of gender, ethnicity and income. Walking plays a crucial role in fostering social interaction and community cohesion (Lund 2002; Gehl 2010). When individuals choose to walk, they are more likely to engage with their surroundings, establishing a sense of belonging and attachment to their local environment (Khabiri, Pourjafar, and Izadi 2020). This active engagement with the neighbourhood facilitates social connections and enhances political involvement, as people become more aware of and invested in local affairs (Lewicka 2005; Leyden 2003). Furthermore, walking contributes to building trust among community members, strengthening social bonds and encouraging collaboration (Leyden 2003). This improved trust is particularly important for older individuals, as it helps to counteract feelings of loneliness and promotes active participation in social life (Khabiri, Pourjafar, and Izadi 2020; Sugihara and Evans 2000). Overall, walking cultivates an atmosphere of community connectedness and supports a more vibrant, inclusive social environment. There is also a positive correlation between walkable neighbourhoods and lower crime rates. Increased pedestrian activity can contribute to natural surveillance (“eyes on the street”), which enhances the overall safety and well-being of the community (J. Jacobs 1961; Gehl 2010).

Furthermore, with walking being the most popular type of moderate-intensity physical activity, it has substantial importance to public health (I.-M. Lee and Buchner 2008). Currently, 31% of the world’s adult and 81% of the adolescent population is insufficiently physically active (WHO 2024). The WHO (2010), therefore, strongly recommends that children and adolescents should do at least an average of 60 minutes per day of moderate- to vigorous-intensity physical activity; adults should do at least 150 minutes of moderate-intensity physical activity throughout the week. It is proven that high walkability and walking accessibility rates lead to increased levels of physical activity (Calise 2013; Cortright 2019; Iravani and Rao 2020) and bring physical as well as mental health benefits to the individuals. Walking leads to improved cardiovascular fitness and muscle strength (P. Kelly, Murphy, and Mutrie 2017) and prevents heart and circulatory diseases, diabetes, obesity and other chronic diseases (I.-M. Lee and Buchner 2008; Iravani and Rao 2020). Furthermore, walking reduces stress and the risk of depression (WHO 2020) and promotes good mental health, overall well-being, self-esteem, cognitive functioning, positive mood and quality of life (P. Kelly, Murphy, and Mutrie 2017). Thus, walking can equally serve to relax and regenerate individuals while moving them from one place to another (Alves et al. 2020; Southworth 2005). A population with a high walking mode share is likely to be healthier, with a lower mortality risk (WHO 2020).

2.1.2. Economic benefits

Walking is the only means of transport that does not require the use of tools or equipment, thus enabling independent movement for young and old (FGSV 2014). Pedestrians move slowly, giving them plenty of time to experience and interact with their urban environment and make spontaneous decisions, such as walking into a shop with interesting products in the window. Moreover, walking is an energy-efficient and cost-effective means of transport for individuals and governments alike. Walking brings cost savings to pedestrians, as it is entirely free and relies solely on human power. Thus, no public transport fees, fuel, vehicle operating costs, vehicle ownership costs, or parking costs are required. The saved money can be spent on local shops and leisure activities. Therefore, walkable environments lead to improved local economic performance (Jou 2011; Leinberger and Alfonzo 2012; Zandiatashbar and Hamidi 2018) and promote wealth (Florida 2014; Oishi, Koo, and Buttrick 2019). On the governmental side, costs for providing, operating and maintaining the infrastructure are minimal compared to roads or public transportation systems. Higher walking shares also reduce the external costs on emissions, accidents, land use, congestion, noise and health effects (Litman 2022; Schröder et al. 2023). While each kilometre driven by car incurs an external cost of €0.11, walking represents benefits of €0.37 per kilometre (Gössling et al. 2019). As a result, spendings on transportation and its negative effects can be minimised.

2.1.3. Environmental benefits

In Germany, 55 hectares are sealed per day, 14% of which is for transport-related infrastructure (Umweltbundesamt 2023). The continuous sealing of natural soil destroys valuable ecosystems and reduces biodiversity. Furthermore, impervious surfaces prevent the natural soaking of rainwater into the ground and thus contribute to flooding events. In the urban environment, impervious surfaces reinforce the heat island effect (Litman 2022; Morabito et al. 2021) and thereby also exacerbate heat waves, which are forecasted to become more frequent and more intense through global warming. This leads to further heat stress for plants as well as humans and negatively affects the health and well-being of urban residents (Tan et al. 2010). As walking only involves moving people and no additional vehicles to move and park, pedestrians need the least amount of space compared to other road users (Nello-Deakin 2019; Gössling 2020). Hence, the promotion of walking can minimize space consumption and all the related negative effects.

Walking only generates CO_2 from human respiration. Besides this, it does not produce greenhouse gases or any other type of air pollution, either directly or indirectly. As the transport sector is one of the main greenhouse gas emitters, an increase in the share of walking could be a significant contribution to the reduction of transport emissions. By providing high local accessibility, a shorter trip on foot can replace a longer trip by car (FGSV 2014). Furthermore, as walking is the main feeder for public transport, appropriate walking conditions are also necessary to enable a higher share of public transport, which is an important complement to ensure regional accessibility. All in all, the promotion of walking is a key element in achieving a more sustainable transport sector.

Unlike motorised modes, walking does not cause pollutants such as NO_x, SO_2, CO and PM_{10}, reducing the negative impact on the environment. Furthermore, since no fossil fuels are needed, all the pollution and environmental damage associated with their extraction, transport and combustion can be avoided (Komanoff 1993).

2.2. Walking needs

In order to increase walking rates, it is necessary to understand the drivers and needs. Therefore, several authors have used and adapted Maslow's hierarchy of needs (1943). Maslow defined five sets of basic needs (physiological needs, safety needs, love and belonging, esteem, self-actualisation) that are interrelated and organised into a hierarchy or pyramid, in which the most primary needs lie at the bottom, and the highest-order needs lie at the top. The pyramid can be used to, first, understand the motivation for starting a walking trip, from bottom to top e.g.: to fulfil physiological needs such as buying food, to fulfil safety needs such as visiting a doctor, to fulfil love and belonging such as visiting family, to fulfil esteem such as going on a hike, or to fulfil self-actualisation such as visiting a spiritual site (Mokhtarian, Salomon, and Singer 2015). Secondly, the general human needs can be transferred to the needs of pedestrians on their way to their destination. The characteristics of the paths and their surrounding have a direct impact on mode (Boulange et al. 2017) and route choice (Mateo-Babiano 2003; Koh and Wong 2013). Therefore, in sum, all steps of the four-step model of travel demand (Hensher and Button 2007) are affected by human needs.

When transferring Maslow's hierarchy of needs to the walking needs, *Figure 2* emerges[3].

Figure 2: The concept of the hierarchy of walking needs (Source: adapted from Alfonzo (2005))

The basic requirement for walking is *feasibility*, which refers to the practicality or viability of a walking trip (Alfonzo 2005). When feasibility is given, *accessibility* is the next fundamental need. This includes urban characteristics such as the connectivity of paths and the availability of destinations. On top of accessibility are the higher-level needs *security and safety*, *comfort* and *pleasurability*. These can be summarised by the term *walkability*. In order to encourage people to walk, it is therefore necessary to ensure general feasibility, accessibility and walkability. As a minimum of walkable infrastructure is available in almost all places, feasibility depends mainly on personal characteristics that cannot be influenced but can only be taken into account through urban and transport planning. Therefore, accessibility and walkability are the two key elements that planners can address.

2.3. Accessibility

The following sections explain how accessibility can be defined (*Section 2.3.1*), how accessibility can be measured (*Section 2.3.2*) and why the results of existing accessibility measures do not match the perceived levels of accessibility *(Section 2.3.3*).

[3] Contrary to Maslow's (1943) original hierarchy of needs, when applied to walking, safety needs are one level higher. Not because it's less important. Just because there are more fundamental needs for pedestrians that need to be fulfilled first.

2.3.1. Definition

"Accessibility is […] a slippery notion, however; one of those common terms that everyone uses until faced with the problem of defining and measuring it!" (Gould 1969, p. 64)

Accessibility was first defined by Hansen (1959, p. 73) as "the potential of opportunities for interaction", focusing on the *proximity* to destinations. These characteristics are also reflected in Tobler's first law of geography: "Everything is related to everything else, but near things are more related than distant things" (Tobler 1970, p. 236). In subsequent years, the definition of accessibility was broadened from mere proximity to include the *ease* with which the destinations can be reached (Dalvi and Martin 1976; Koenig 1980; Niemeier 1997). In 2000, the definition was further expanded by Bhat et al. (2000, p. 1) to "a measure of the ease of an individual to pursue an activity of a desired type, at a desired location, by a desired mode, and at a desired time", now including the *ease of an individual*. Following this, Geurs and van Wee (2004, p. 128) defined accessibility as "the extent to which land-use and transport systems enable (groups of) individuals to reach activities or destinations by means of a (combination of) transport mode(s)" and cluster its influential factors into four components: land-use, transportation, temporal and individual (see *Figure 3*).

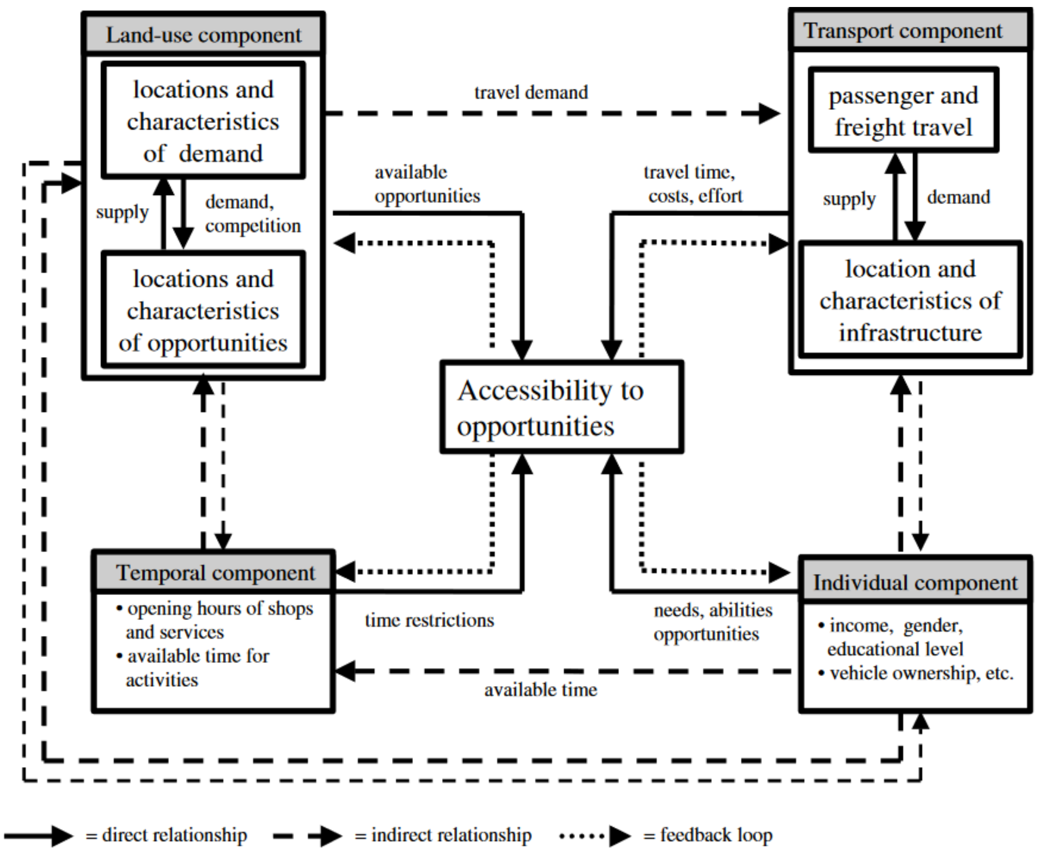


Figure 3: Relationships between components of accessibility (Source: Geurs and van Wee (2004))

The *land-use component* refers to the location and characteristics of opportunities and demand. The *transportation component* reflects the transport system that makes it possible to travel from the source of demand to the desired destination and includes the required time, effort and (generalised) costs. The *temporal component* describes the availability of opportunities at different times of the day, and the time available for individuals to participate in certain activities which is mostly influenced by opening hours, individual time budgets and temporal changes in the transportation component, such as the illumination of footpaths. The *individual component* reflects personal needs, capabilities and preferences that influence the other three components. Hence, the individuals have assumed a central role in the accessibility concept.

According to Handy and Niemeier (1997), the key is to measure accessibility in terms that matter to people in their assessment of the options available to them. As this thesis focuses on walking accessibility, the key is to assess to what degree the walking accessibility meets people’s needs.

2.3.2. Accessibility measures

There are various approaches for measuring accessibility. First, based on the intended research questions, different perspectives can be applied. With referring back to the four accessibility components, the land-use and transportation components mainly describe the *place*, while the individual and temporal components mainly capture how *people* with individual preferences and differing temporal constraints can access destinations. In this context, the terms *place-based accessibility* and *people-based accessibility* are used to specify these two perspectives (Miller 2005). *Place-based accessibility* measures focus on the spatial separation between places of origin, such as home or work, and potential places of activity, such as commercial areas, education or healthcare facilities (Kwan and Weber 2003; Miller 2005). Within *place-based accessibility*, it can be further distinguished between *infrastructure-based measures*, which are mainly used for analysing the performance of the transport infrastructure, and *location-based measures,* which analyse the accessibility at locations (Geurs and van Wee 2004).

People-based accessibility, on the other hand, focuses on people as individuals and can be operationalised through two approaches*: Person-based measures* are used in the context of time-geography (Hägerstrand 1970) and focus on how the individuals move in space and time (Miller 2005). They take into account certain constraints, such as the capabilities of a person. *Utility-based measures* are founded in the economic theory and analyse the benefits that people derive from access to spatially distributed activities (Geurs and van Eck 2001).

Following the aim of this thesis – to support planners in designing cities with attractive walking accessibility to all daily needs for all people – the location-based measures offer a suitable perspective. Location-based accessibility can be conceptualised using the following mathematical expression (Geurs and van Wee 2004):

$$\boldsymbol{A_i = \sum_j D_j f(c_{ij})} \qquad (1)$$

A_i: Accessibility of place i

D_j: Destination potential found at location j

c_{ij}: Generalised costs of travelling (**walking**) between i and j

$f(c_{ij})$: The impedance function applied to the generalised costs of travel between i and j

Typical location-based calculation measures are *contour* and *gravity-based* measures (Geurs and van Eck 2001; Handy and Niemeier 1997; Iacono, Krizek, and El-Geneidy 2010). *Contour-based measures* (also known as *cumulative opportunities*, *isochrones*, etc.) show the number of opportunities that can be reached from one point within a certain distance, time interval or costs. They are valued for their easily interpretable results (Geurs and van Eck 2001; Albacete 2016), but have the drawback of not distinguishing between different travel times within the cut-off range (Bertolini, le Clercq, and Kapoen 2005), as they follow basic impedance functions, such as (El-Geneidy and Levinson 2006):

$$\boldsymbol{f(c_{ij}) = \begin{cases} 1 & for\ c_{ij} \leq c_{max} \\ 0 & else \end{cases}} \qquad (2)$$

Gravity-based measures (also known as *potential measures*, *Hansen-type measures*, etc.) additionally take into account that people are more likely to visit closer destinations than more distant ones (Geurs and van Eck 2001). Therefore, specific impedance functions, such as the *negative exponential* and the *modified Gaussian* functions, are used (Kwan 2010). As impedance values, different generalised costs terms, such as time (Pajares 2022), emissions (Kinigadner 2020) or monetary costs (Büttner 2016), can come into play. Thereby, each of the accessibility components – transport, land-use, individual, and temporal – can have an independent or combined effect on the impedance along a given route.

Accessibility measures can be integrated into planning instruments, which “can play a valuable role in urban planning practice by providing a practical framework for exploring and testing relationships between land use and transport infrastructure” (te Brömmelstroet et al. 2016,

p. 1). While urban and transport planners have widely found value in accessibility instruments (te Brömmelstroet, Silva, and Bertolini 2015), a decade ago, many barriers, such as limited data availability, prevented practitioners from actually using accessibility measures (Papa et al. 2015). However, as these barriers are increasingly being resolved, Handy (2020) stated that the time for accessibility measures has now come.

2.3.3. Perceived accessibility

> *"In reality, accessibility is only as good as the ease with which people experience the services and activities, but this has received little research attention."*
> *(Jamei et al. 2022, p. 18)*

Besides accessibility measures that calculate accessibility levels based on spatial data, there are also accessibility studies that attempt to assess perceived accessibility levels through surveys or reported data. *Perceived accessibility* (also known as *self-reported accessibility, subjective accessibility* or *experienced accessibility*) can be defined as "how an individual, or groups of individuals, understand or experience their own accessibility." (Curl 2018, p. 1148)

Although already Morris et al. (1979), Koenig (1980), Handy and Niemeier (1997), Geurs and van Wee (2004) and Bertolini et al. (2005) stated that accessibility is influenced by individual experiences and emphasised that personal capabilities and perceptions should be considered in accessibility measures, conventional location-based accessibility measures still focus on the land-use and transport component and mainly neglect the individual component (Albacete 2016; Jamei et al. 2022). The measures therefore use travel time or distance but ignore how an individual perceives their journey time (Curl 2018; Lättman, Olsson, and Friman 2018). As a consequence, many studies found a mismatch between the calculated results and the actual perceptions (Curl, Nelson, and Anable 2015; Damurski, Pluta, and Zipser 2020; Gebel et al. 2011; Lättman, Olsson, and Friman 2018; McCormack et al. 2008; Pot, van Wee, and Tillema 2021; J. Ryan and Pereira 2021; M. Ryan et al. 2016; van der Vlugt, Curl, and Wittowsky 2019; van der Vlugt, Curl, and Scheiner 2022). This leads to an overestimation of accessibility levels (Krizek, Horning, and El-Geneidy 2012; Curl, Nelson, and Anable 2015; González et al. 2015; J. Ryan and Pereira 2021). The reason for this is the missing perception of different user groups in the calculated accessibility measures (Krizek, Horning, and El-Geneidy 2012; Curl 2018; Pot, van Wee, and Tillema 2021; Jamei et al. 2022). This discrepancy means that the calculated accessibility results can be systematically inaccurate and do not represent certain population groups (Curl 2018), likely vulnerable groups that are already disadvantaged.

In order to overcome these discrepancies, more accurately calculated accessibility measures are needed to serve as a proxy for perceived accessibility (Pot, van Wee, and Tillema 2021). Therefore, several authors argue for the need to consider individual perceptions in the measure by integrating the sensitivity to the urban environment and differences among individuals (Kwan and Weber 2003; Albacete 2016). In summary and applied to pedestrian accessibility, this means, that the individual needs, capabilities and preferences of the people should be included in future accessibility measures.

2.4. Walkability

The following sections explain, how walkability can be defined (*Section 2.4.1*), what attributes influence it (*Section 2.4.2*) and give an overview of existing walkability measures (*Section 2.4.3*).

2.4.1. Definition

The term *walkability* describes how walking-friendly an area is. Depending on the context, various definitions come into play (cf. Bucksch and Schneider 2014; Barrera-Fernández and Hernández-Escampa 2020). However, most of them name "safety", "comfort" and "pleasurability" as key elements (American Planning Association 2006; Litman 2003; Spoon 2005; Tsiompras and Photis 2017). Thus, in this thesis, *walkability* is defined as the extent to which paths are safe, comfortable and pleasurable for people of all abilities to walk. Some definitions of walkability also include the terms "accessibility", "connectivity" and "presence of destinations" (e.g. Southworth 2005; Spoon 2005; Lo 2009), demonstrating the strong links and sometimes fluid boundaries between the concepts of accessibility and walkability. However, referring back to *Figure 2*, in the context of this thesis, walkability is seen as being on top of accessibility. Walkability is part of accessibility, but not the other way around.[4]

Walkability provides what is lacking in current location-based accessibility measures: attractiveness of paths, environmental influences and user perceptions.

2.4.2. Influencing factors

Many studies have proven that walkability has a positive impact on walking behaviour (Carver et al. 2005; De Vries et al. 2010; Owen et al. 2004; Timperio et al. 2004; Wendel-Vos et al. 2004) and it is widely acknowledged that pedestrians have specific demands on their

[4] This understanding was developed during the course of this thesis. The definitions in the publications may, therefore, be different (cf. *Section 8.2.2*).

environment, which are not restricted to distance, time or financial cost (Jonietz and Timpf 2012).

Walkability is influenced by various macro and micro scale factors. Following the logic of *Figure 2*, a *safe* and *secure* walking infrastructure that prevents people from being exposed to any kind of fear or risk is the basic requirement for making people walk. *Traffic safety* and protection from road impacts are determined by factors such as the number of car lanes (Ewing 1999; Southworth 2005; Speck 2013), the traffic load (McGinn et al. 2007; Hillnhütter 2016; Moura, Cambra, and Gonçalves 2017; Ortega et al. 2021), the proportion of heavy goods vehicles (Saelens et al. 2003; Arslan et al. 2018) and the driven speed (Saelens et al. 2003; Alfonzo 2005; Southworth 2005; McGinn et al. 2007). The extent to which pedestrians are exposed to the effects and dangers of traffic depends on the spatial separation of footpaths from the road (Saelens et al. 2003; Hillnhütter 2016) and the number and design of street crossing possibilities (Handy and Clifton 2001; Lo 2009; C. E. Kelly et al. 2011; Wimbardana, Tarigan, and Sagala 2018; Hoogendoorn and Bovy 2004; Moura, Cambra, and Gonçalves 2017). Besides traffic safety, *social security* is highly important, especially during night-time. A lively environment with many “eyes on the street” can increase perceived security (Gehl 2013; J. Jacobs 1961), whereas low visibility of sidewalks, such as in underpasses (Hillnhütter 2016), areas with dense vegetation (Golan et al. 2019), or low lighting levels (Saelens et al. 2003) can decrease it.

When safety and security are given, it plays a role if the infrastructure is properly designed to make walking comfortable. Walking *comfort* is influenced by factors such as sidewalk width (Moura, Cambra, and Gonçalves 2017), surface and smoothness (Wimbardana, Tarigan, and Sagala 2018), path slope (Clifton, Livi, and Rodriguez 2007), freedom from barriers (Arslan et al. 2018) and the presence of shelter and shade to protect from sun and rain (Pilipenko, Skobeleva, and Bulgakov 2018).

On top of this, an enjoyable and diverse surrounding makes walking pleasant. *Pleasurability* is, among others, influenced by land use (Gao et al. 2022), architectural attractiveness (Lo 2009), the presence of vegetation (Hillnhütter 2021) and water (Rafiemanzelat, Emadi, and Kamali 2017), and the cleanliness of an area (C. E. Kelly et al. 2011).

2.4.3. Walkability measures

As walkability is influenced by a multitude of attributes, a multiple-criteria analysis is needed to measure and evaluate it. There are various methods trying to cover this challenge and assess walkability. Based on the aim of the study and the definition of walkability, different attributes that influence walkability are assessed, ranging from macro-scale features such as land use to micro-scale elements such as the availability of litter bins. Overall, “there is no universal consensus about an exhaustive set of criteria to consider” (Blečić, Congiu, et al. 2020, p. 12). Following the fluid boundaries between the definitions of accessibility and walkability, many walkability measures also see accessibility as part of it (e.g. Walk Score ® (Walk Score 2011)), but usually treat accessibility to certain destinations and street connectivity just as additional walkability attributes, next to safety, security, comfort and pleasurability attributes (Venerandi et al. 2024).

Because walking conditions, environmental settings and personal habits vary widely around the world, it is crucial to tailor walkability measures to the geographical context. For example, residents of a small village in the African jungle may define their walkability needs very differently from residents of a car-dependent US suburb. The majority of the existing measures were developed in North America (e.g. Walk Score ®, Neighbourhood Environment Walkability Scale – NEWS (Saelens et al. 2003), Pedestrian Level of Service (Landis et al. 2001), Walkability Index (Bradshaw 1993)) and Europe (e.g. Active for Life – A4L (Wilcox et al. 2008), Capability-Wise Walkability Score – CAWS (Blečić, Cecchini, et al. 2020), OS-WALK-EU (Fina et al. 2022)). Some are developed in Asia (e.g. Environment in Asia Scan Tool - Hong Kong version – EAST-HK (Cerin et al. 2011)) and Australia (e.g. Systematic Pedestrian and Cycling Environmental Scan – SPACES (Pikora et al. 2002)). So far, no measures developed in Africa and South America have been found. The measures not only differ in their geographical development context; they also differ in scale. The majority of the found measures are on neighbourhood-scale (e.g. MAPS-global (Cain et al. 2018)), while a few are on street-level (e.g. SPACES).

Same as for accessibility, the walkability measures can be clustered into calculated and perceived measures (Lin, Sun, and Li 2015). Calculated measures (e.g. MAPS-global) calculate an index using spatial data. Perceived measures (e.g. NEWS) are based on questionnaires conducted for a respective study area. In addition, combined approaches can be found (e.g. Walkability Audit Tool (Dannenberg, Cramer, and Gibson 2005)). Perceived measures are thereby more often on a small-scale, while objective measures tend to be more aggregated. Furthermore, the perceived walkability measures tend to be more extensive while the majority of calculated walkability measures take into account only some of the many influencing attributes.

Overall, walkability measures are subject to similar shortcomings as accessibility measures. Studies have shown that there are partly low correlations between calculated and perceived walkability measures (McGinn et al. 2007; Gebel et al. 2009; Golan et al. 2019), due to lack of complexity but also as the individual characteristics are mostly neglected in calculated walkability measures. Furthermore, the measures may not be able to represent other spatial contexts. Several authors therefore argue for the need to develop more complex walkability measures that accurately represent walkability in all its diversity (Maghelal and Capp 2011; Grob and Michel 2011; Golan et al. 2019; De Vos et al. 2022), take into account different user groups in terms of age, gender, capabilities and preferences (Blečić et al. 2015; Grob and Michel 2011; Fancello, Congiu, and Tsoukiàs 2020; Jonietz and Timpf 2012; Chan, Schwanen, and Banister 2021), and are adaptable to local contexts (Blečić, Congiu, et al. 2020; Spittaels et al. 2009; Chan, Schwanen, and Banister 2021; Fancello, Congiu, and Tsoukiàs 2020) to achieve higher reliability. To summarise, the requirements are similar to those of the accessibility measures but appear to be more sensitive to geographical differences and small-scale complexity of the urban environment. Venerandi et al. (2024) argue that a weighting of these walkability attributes is inevitable, either by using weightings derived from prior evidence and summarised by, e.g. the Analytic Hierarchy Process (AHP) method or by customising the weights through local questionnaire results.

2.5. User needs

The following sections elaborate on the capability approach (*Section 2.5.1*) and how it can serve as a theoretical framework to incorporate user needs in walking accessibility measures (*Section 2.5.2*).

2.5.1. Capability approach

When trying to understand people's needs influencing individual walkability and perceived accessibility, the capability approach by Nussbaum (2003) offers a suitable framework. According to Sen (1980), *capabilities* cover what people are actually able to do and to be, not only what they have done or become (Lewis, MacKenzie, and Kaminsky 2021; Vecchio and Martens 2021). Capabilities thus show the potential opportunities of people (Alkire 2005); they follow a similar logic to the concept of accessibility but instead of being limited to spatial accessibility, they are applied to all dimensions of life. The individual capabilities of a person are based on internal and external factors: 1) the intrinsic abilities of a person, detained but not necessarily exercised, to do and to be, and 2) the opportunities and presence of external conditions which make the exercise of that power possible (Blečić et al. 2013). In order for a person to be capable of doing something, e.g. walking to a specific destination, both the internal and external factors need to be in line. This applies to all five levels of the walking needs (see *Figure 4*); ideally, for all of them, the external factors should match the internal ones to fully meet a person's needs.

Figure 4: Application of the capability approach to the walking needs

2.5.2. Internal factors of walking accessibility

"Understanding how space and the environment influence citizens' preferences and values is a fundamental step for designing legitimated public policies."
(Fancello, Congiu, and Tsoukiàs 2020, p. 29)

All people have different personal characteristics, such as gender, age, physical and mental condition, and lifestyle. These can change over the course of a lifetime, but also at different times of the day, e.g. depending on the weather, mood and purpose of the trip. Depending on those individual and context-specific factors, people develop different needs, capabilities and preferences that affect walking accessibility (Chan, Schwanen, and Banister 2021; J. Ryan and Pereira 2021).

Previous studies found that socio-demographic characteristics, such as education level (Marquet, Bedoya, and Miralles-Guasch 2017; Arvidsson et al. 2012; Gebel et al. 2009), employment status (Marquet, Bedoya, and Miralles-Guasch 2017), income (van der Vlugt, Curl, and Scheiner 2022; Ma and Cao 2019), wealth (Manaugh and El-Geneidy 2011), age (Marquet, Bedoya, and Miralles-Guasch 2017; Trichês Lucchesi et al. 2021; van der Vlugt, Curl, and Scheiner 2022; Gebel et al. 2009), gender (Ma and Cao 2019; Chor et al. 2016; Suarez-Balcazar et al. 2020) and ethnicity (Adkins et al. 2019) can influence how people perceive walking accessibility. However, the various studies came to different clear results. User-specific perceptions have, therefore, not yet been fully understood. It is clear that perceived accessibility is influenced by individual factors, but not by which exactly and to which extent. Thus, further research to explore how walking accessibility is perceived by different user groups is necessary. Furthermore, it seems auxiliary to examine which additional factors might influence the results.

2.6. First approaches that combine walking accessibility, walkability and user-specific needs

When searching for existing studies and methods that combine accessibility, walkability and user-specific needs, some first approaches can be found.

2.6.1. Walking accessibility and walkability

On the integration of walkability attributes in accessibility analysis, some researchers such as Jonietz and Timpf (2012), Anciaes, Nascimento, and Silva (2015), D'Orso and Migliore (2018), Erath et al. (2017) and Blečić, Cecchini, and Trunfio (2018) have developed first approaches in which walkability attributes have been integrated into walking accessibility measures. However, they assumed that walkability is the same for all pedestrian groups.

2.6.1. Walking accessibility and user-specific needs

Focussing solely on accessibility, some user group specific walking accessibility studies were found. For example, García-Palomares, Gutiérrez, and Cardozo (2013) use different walking distance thresholds and decay functions for different age groups. Cheng et al. (2019) investigate walking accessibility to recreational amenities for elderly people by using adaptive thresholds for walking distances. Both focus on the fact that accessibility changes as a consequence of differences in individual willingness to reach destinations (Arranz-López et al. 2019); however, they did not include walkability attributes.

2.6.2. Walkability and user-specific needs

Likewise, some user-specific walkability studies were found. For example, Moura, Cambra, and Gonçalves (2017) measure walkability for four different pedestrian groups: children, adults, seniors and impaired pedestrians. Beale et al. (2006) developed customisable routing for wheelchair users, which takes slope, surface and obstacles into account as impedances. Golan et al. (2019) developed the Women's Walkability Index, which is a calculated measure specifically shaped to represent the walking needs of women. Furthermore, the walkability survey NEWS was adjusted to serve the needs of different user groups, such as the NEWS-Y for youth (Rosenberg et al. 2009), the NEWS-CC for Chinese children (He et al. 2021) or the NEWS-CS for Chinese seniors (Cerin et al. 2010). Additionally, Fancello, Congiu, and Tsoukiàs (2020) adjusted the CAWS method to match eleven different population groups by assigning user group specific weights to the different walkability attributes. Chan, Schwanen, and Banister (2021) developed an approach to assess walkability for different population groups by considering 71 attributes and summing/multiplying them in different ways per population group.

However, the authors highlighted the need for future research to identify and incorporate the walkability attributes more comprehensively (Golan et al. 2019; Chan, Schwanen, and Banister 2021) and apply them to further population groups (Chan, Schwanen, and Banister 2021; Fancello, Congiu, and Tsoukiàs 2020).

2.6.1. Walking accessibility, walkability and user-specific needs

Two recent studies were found that consider all three – accessibility, walkability and differentiation per user group. Amaya et al. (2022) assessed accessibility for three different user groups: older adults in good health, older adults with a chronic disease, and older adults with reduced mobility. To do so, they considered the pedestrian network, facilities and shops, public benches, slopes and gradients. Gaglione, Cottrill, and Gargiulo (2021) measured the accessibility of older adults by taking ten walkability attributes into account (slope, sidewalk width, surface, illuminance, traffic volume, presence of escalators, presence of benches, presence of green areas, presence of panoramic points, road type). However, both studies point out the limitation that only selected walkability attributes were considered and see a need for further measure development that includes additional walkability attributes. In order to realise this, the influencing attributes and their relevance must first be better understood.

2.7. Intermediate conclusions

In summary, walking brings many positive effects for society, individuals and the environment, which can counteract many challenges that humanity currently faces. In order to increase the number of trips made on foot, the infrastructure and environment must meet the walking needs of the individual persons. In general, accessibility measures provide planners and decision makers with helpful analysis to better plan for specific modes and guarantee adequate accessibility to important destinations. However, for the means of walking, accessibility analyses are not yet capable of generating comprehensive results. There is clear evidence that walking accessibility is influenced by walkability attributes and individual needs, but this is not reflected in the accessibility measures. Current walking accessibility measures lack the inclusion of walkability attributes and user perceptions, which leads to the fact that the calculated results do not match the perceptions of the people. Future measures should address these shortcomings by increasing the level of detail, while at the same time being easily transferable and adaptable to local contexts.

3. Research design

The aim of this dissertation is to develop a measure that can represent walking accessibility more realistically than existing methods. It follows the hypothesis that one accessibility index alone is not sufficient to represent all individual needs, capabilities and preferences. Rather, a variety of user-specific measures is required.

3.1. Methodological approach

Methodologically, the measure is based on the four accessibility components (cf. *Figure 3*). While conventional location-based walking accessibility models mainly include the land-use and transportation components, this dissertation develops an approach that also includes the individual component by modelling its influences on the transportation component. *Figure 5* presents an adapted version of *Figure 3* that is tailored to walking accessibility and highlights the influencing factors on which this work focuses.

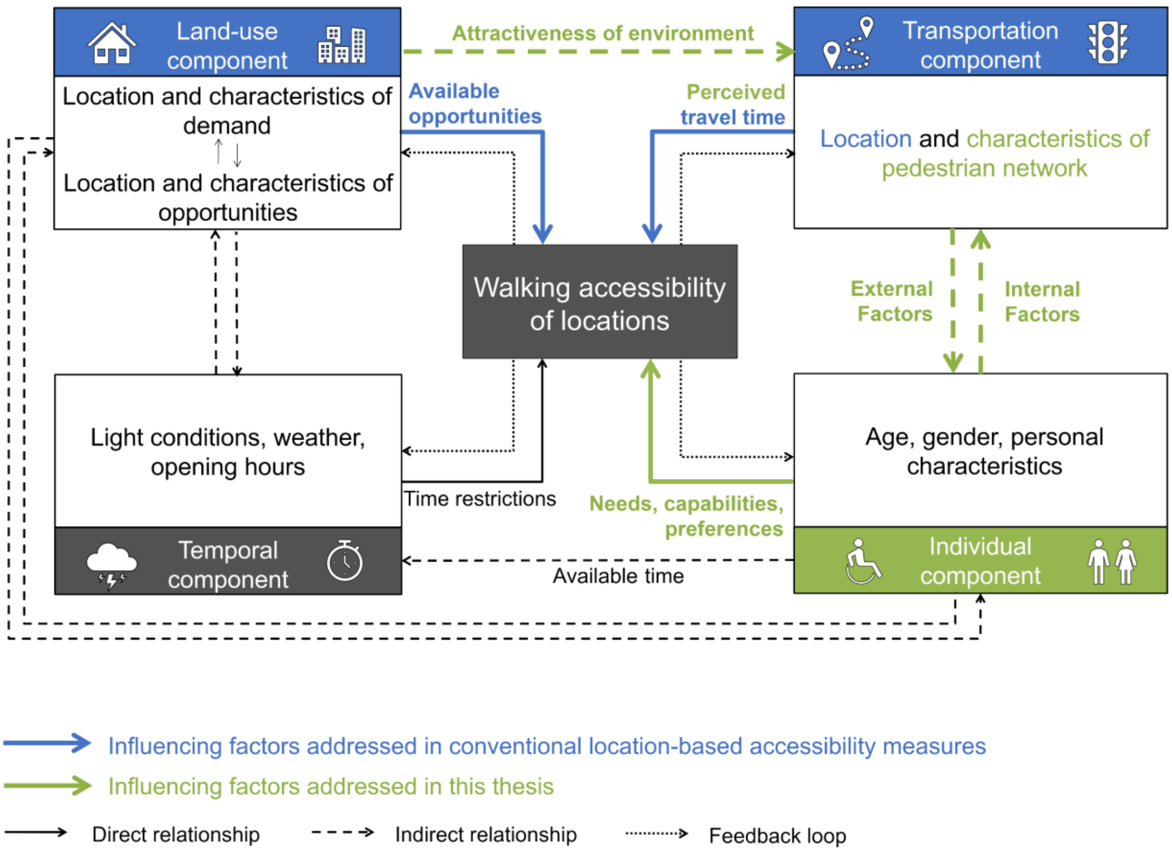


Figure 5: Contribution of this dissertation to modelling the four accessibility components (Source: adapted from Geurs and van Wee (2004))

Explanation of the graphic: Contribution of this dissertation to modelling the four accessibility components

Conventional location-based accessibility measures are mainly limited to the land-use and the transportation component, whereby the land-use component describes the demand (e.g. population) and supply of opportunities (e.g. supermarkets) and the transportation component represents the physical connection between the locations of demand and supply, i.e. the pedestrian network. This dissertation goes one step further by not only modelling the location of the walking paths but also considering its characteristics, such as sidewalk width, surface qualities and illuminance. The walking infrastructure thereby represents the external factors of the capability approach (cf. *Section 2.5.1*). Those need to match with the internal factors of the individual component, such as age, gender, personal characteristics and resulting needs, capabilities and preferences. For instance, if a person is mobility-impaired and sits in a wheelchair, but the infrastructure is not barrier-free, then there is a mismatch between external and internal factors, which makes a path unusable for this person. Furthermore, this dissertation considers that the land-use component not solely influences demand and supply of destinations but at the same time also represents the walking environment, which has an impact on the attractiveness of paths. For example, a mixed-use area with many diverse shops, amenities and high liveliness has a positive impact on walkability.

In order to achieve an easily transferable measure, a calculated approach seems suitable. The steadily increasing availability of open geodata makes it possible to gradually increase the accuracy of the calculated measures and even include micro-level features. However, as it is crucial to also take the perceptions into account in order to achieve realistic results, these first need to be analysed (RQ 2) and then transformed into numeric values (RQ 3).

3.2. Research steps

To develop such a method, the following three research steps will be carried out:

1. *Understand* how current measures are constructed, what they consider and what they are missing. (RQ 1)

2. *Analyse* which attributes have an impact on perceived walking accessibility. (RQ 2)

3. *Develop* a walking accessibility measure that includes walkability attributes and individual needs. (RQ 3)

For each of these steps, a number of research activities have been carried out (see *Figure 6*).

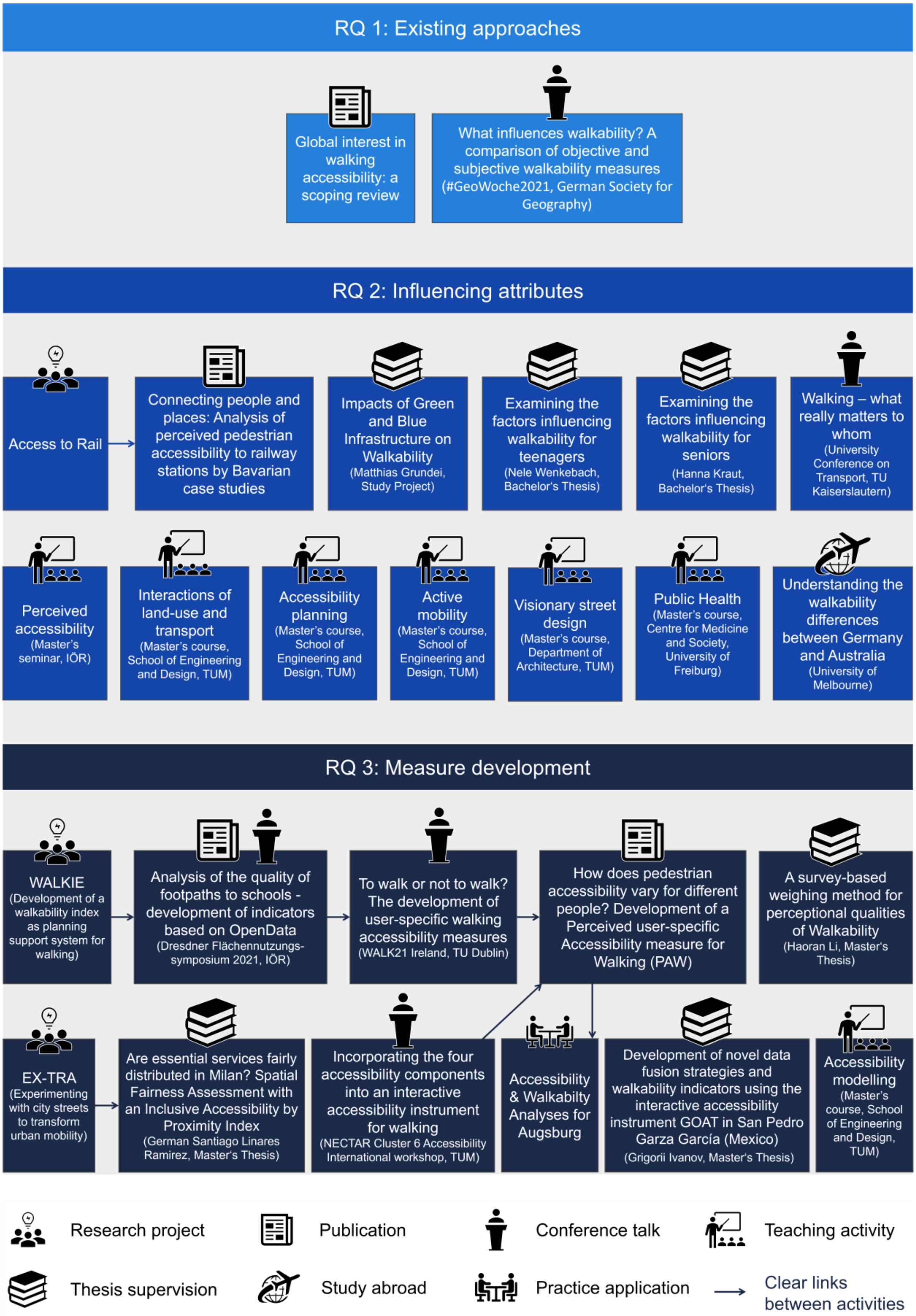


Figure 6: Research activities that contributed to answering the research questions

Some of these, especially in the method development, clearly built on each other, while others rather helped to generate a comprehensive understanding and tried new approaches. Some activities also contributed across the research questions. These have been included in the section where they contributed the most.

As the research activities took place in different locations, *Figure 7* shows where on-site activities contributing to RQ 2 and/or RQ 3 were conducted. The literature reviews of RQ 1 were not linked to a specific location and thus were not added to the map.

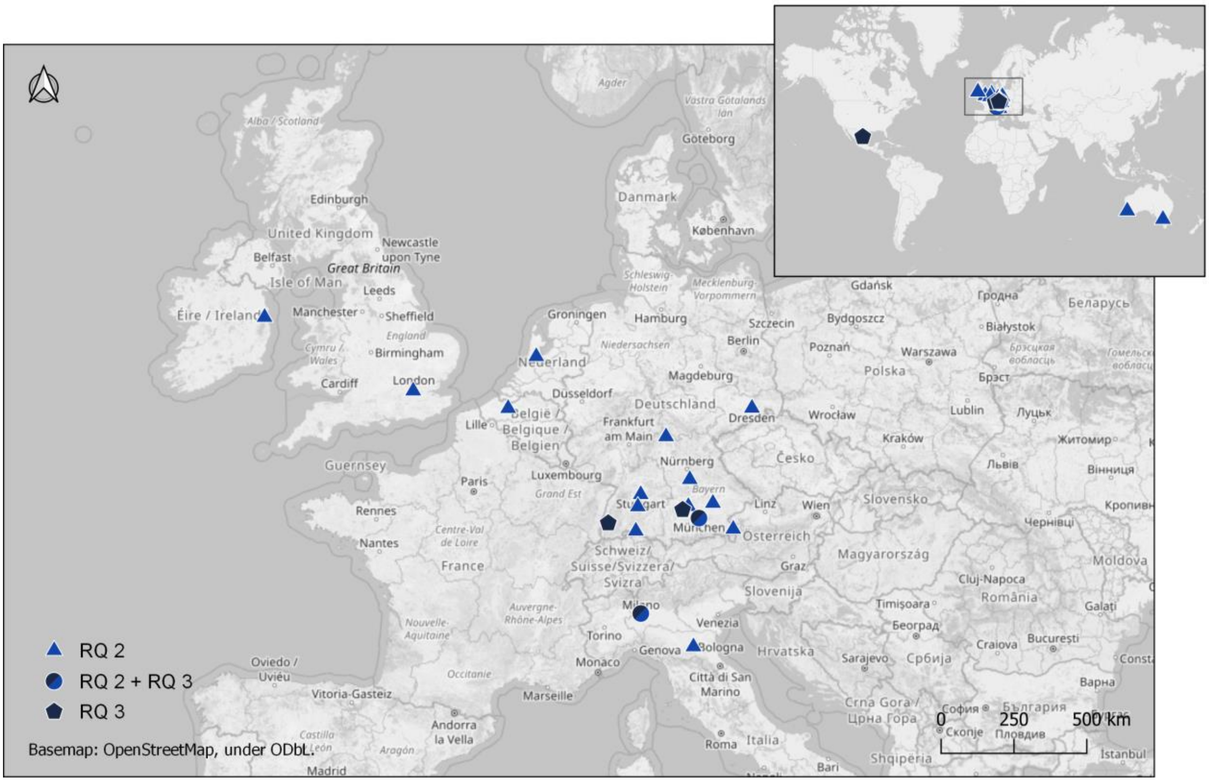


Figure 7: Localisation of the research activities

3.2.1. RQ 1: Existing approaches

RQ: Which walking accessibility studies exist, what do they consider and what are they missing?

→

Aim: to better *understand* how current measures are constructed, what they consider and what they are missing.

To answer this first research question, a systematic scoping review of the academic literature concerning walking accessibility was conducted. The term *walking accessibility* was distinguished from the broader topic of *walkability* by two criteria: papers must consider one or more destination type(s), and papers must address the issue of distance or impedance.

85 papers that met these criteria were found and examined along the four accessibility components, the included impedance and if the used measure is calculated (*objective*) or perceived (*subjective*)[5]. The results can be found in *Chapter 4*.

As walkability is an important part of walking accessibility, also walkability measures were reviewed. In total, over 60 existing measures were found, thematically clustered and assessed which walkability attributes were considered. The findings were presented and discussed with the scientific audience at the #GeoWoche2021 conference. Selected results from this review can also be found in *Section 6.2*.

In both reviews, literature was collected on a global level, though limited to research items being available in English or German.

3.2.2. RQ 2: Influencing attributes

RQ: Which attributes have an impact on perceived walking accessibility?	⟶	**Aim:** to *analyse* which attributes have an impact on perceived walking accessibility.

The main activities contributing to the second research question happened as part of the project “Access to Rail” (03/2017 – 12/2018). Within this project, on-site and online surveys with 754 valid answers were conducted in five Bavarian towns (Germany). The results were compared with calculated accessibility analyses. Additionally, statistical analyses were performed to understand the importance of different attributes influencing perceived walking accessibility and how this differs between different people and places. The results can be found in *Chapter 5*.

The author also worked on the research project “EX-TRA (EXperimenting with city streets to TRAnsform urban mobility)” (03/2020 – 02/2024), which aims to create a proactive vision of cities that are attractive and inclusive for cycling and walking. The project included research trips to Bologna (Italy), Milan (Italy) and Ghent (Belgium), and surveys in London (England), Bologna and Munich (Germany) to better understand which micro street elements have an impact on walkability. Interim results and findings were discussed between researchers and practitioners from the six participating cities (Amsterdam (Netherlands), London, Bologna, Milan, Ghent, Munich).

[5] In the earlier stages of this dissertation, the terms *objective* and *subjective* were used to describe the approach of accessibility measures. However, in later stages of the dissertation, the author moved to the terms *calculated accessibility* and *perceived accessibility* (cf. *Section 8.1.3*).

Besides this, further insights regarding specific population groups and walkability attributes were gained through student theses (Krauth 2021; Wenkebach 2022; Grundei 2021) and further teaching activities. In Master's seminars, surveys and focus-group specific analyses on perceived accessibility were conducted to enrich the understanding. Based on the results, four sample user groups with diverse needs were chosen. Their needs, capabilities and preferences were studied in detail through an AHP assessment of existing literature (see *Chapter 7*).

Furthermore, to broaden horizons, the author undertook a one-month research stay at the University of Melbourne (Australia). Several field surveys and interviews were conducted in Melbourne and Perth (Australia) to analyse how the barriers and drivers to walking are changing in different global settings.

The overall results and theoretical approaches were discussed in different stages at the "Universitätstagung Verkehrswesen" (*en: University Conference on Transport*) in 2021 and in several Master's courses.

3.2.3. RQ 3: Measure development

RQ: How can the variety of perceptions be represented in feasible, calculated accessibility measures?	→	**Aim:** *Develop* a walking accessibility measure that includes walkability attributes and user needs.

The measure development was two-fold and builds on an initial approach of incorporating the individual component into the accessibility instrument GOAT (see Pajares 2022; GOAT-Community 2023), which was carried out as part of the author's Master's Thesis (see Jehle 2020). It became clear that a deeper understanding of the factors influencing individual walking accessibility and additional methodological approaches are needed to fully accomplish this aim. Therefore, with the growing insights from RQ 1 and RQ 2, an improved method was developed and gradually enhanced.

As walkability is a key component, first a walkability measure was developed during the "WALKIE (WALKability IndEx)" project (11/2020 – 06/2021). This measure calculates a walkability score per route segment based on security, safety, comfort and pleasurability. It was first developed for the Munich districts "Hasenbergl-Lerchenau Ost" and "Lerchenau West" and then transferred and applied to the City of Freiburg (Germany) and the City of Augsburg (Germany). The results can be found in *Chapter 6*.

In the next step (see *Chapter 7*), the walkability measure was enhanced and incorporated into the final perceived user-specific accessibility measure for walking (PAW). Therefore, WALKIE was refined, adjusted to different user groups and embedded in the accessibility concept by integrating it into the accessibility tool GOAT. On the accessibility side, a contour-based measure was used as a first approach, as it is methodologically simpler than a gravity-based measure and their results are easier to understand. The developed method was applied to the same Munich districts used in the first implementation of WALKIE. Furthermore, parts of the measure were used in a project with the City of Augsburg and the results were discussed with the local practitioners.

Figure 8 shows how the two measures, WALKIE and PAW, are linked to the walking needs pyramid. While WALKIE represents the walkability part, PAW extends the approach to include the accessibility component and matches the internal factors of different user groups with the external factors of the walking infrastructure and environment.

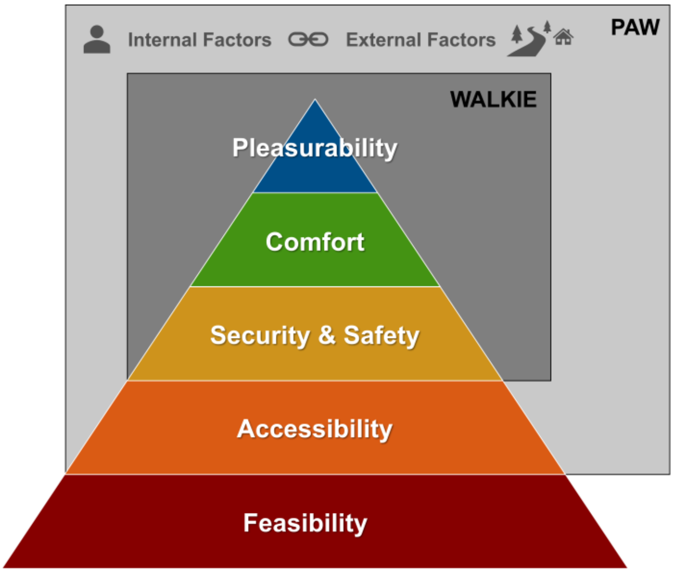


Figure 8: Linking the developed measures with the walking needs

The states of the measure development were discussed at three scientific conferences (NECTAR Cluster 6 Accessibility International workshop 2020, “Dresdner Flächennutzungs-symposium” (*en: Dresden Land Use Symposium*) 2021, WALK21 Ireland 2022) and in a Master’s course.

Further methodological approaches were tried and discussed in the project EX-TRA (see Büttner, Zuñiga, and Jehle 2023; Pucci, Lanza, and Carboni 2021) and in student theses (see Linares Ramirez 2022; Haoran Li 2021; Ivanov 2021).

3.3. Key methods

Table 1 shows a summary of the key methods that were used in the four publications of this paper-based dissertation.

Table 1: Summary of the main methods used

Method	Result	Data	Used in
Literature review	Accessibility measures and their characteristics	85 papers	Publication 1
Literature review	Influencing factors of pedestrian accessibility	>25 papers	Publication 2
GIS analyses	Calculated accessibility of railway stations	Spatial data (OSM, Census)	Publication 2
On-site & online survey	Perceived accessibility of railway stations	754 respondents	Publication 2
Statistical analysis	Influencing factors of perceived accessibility	Survey results (see above)	Publication 2
Literature review	Walkability measures and their characteristics	>50 papers	Publication 3
Data collection	Spatial data on the walking network with micro-features	OSM (enriched), Mapillary (collected)	Publication 3
Measure development	Walkability measure WALKIE	Spatial data (OSM, Mapillary, FreiGIS, ATKIS, UrbanAtlas, Census, etc.)	Publication 3
Literature review	Walkability attributes (overall and for sample user groups)	121 papers	Publication 4
AHP	Weights of walkability attributes for sample user groups	40 papers	Publication 4
Measure development	Accessibility measure PAW	Spatial data (OSM, ATKIS, Census, etc.)	Publication 4

3.4. Linking research questions and scientific publications

This dissertation contains four scientific publications that are presented in *Chapters 4* to *7*. Each of the publications contains its own literature review, methodology, results, discussion, and conclusions section. At the same time, they are contributing to the overall aim of this dissertation by addressing one or more research questions (see *Table 2*).

Table 2: Contribution of the scientific publications to answering the research questions

	RQ 1 Existing approaches	**RQ 2** Influencing attributes	**RQ 3** Measure development
Publication 1 *Global interest in walking accessibility: a scoping review*	**X**	X	
Publication 2 *Connecting people and places: Analysis of perceived pedestrian accessibility to railway stations by Bavarian case studies*		**X**	
Publication 3 *Analysis of the quality of footpaths to schools: Development of indicators based on OpenData*	X	X	**X**
Publication 4 *How does pedestrian accessibility vary for different people? Development of a Perceived user-specific Accessibility measure for Walking (PAW)*		X	**X**

X = main contribution of the publication
X = side contribution of the publication

3.5. List of publications

This section (see *Table 3*, *Table 4*, *Table 5* and *Table 6*) provides an overview of the four publications that are included in this dissertation and are presented in full length in the following *Chapters 4* to *7*.

Table 3: Overview of Publication 1

Publication 1	**Global interest in walking accessibility: a scoping review**
Authors:	Louis A. Merlin & Ulrike Jehle *Both authors contributed equally to this article.*
Accepted:	27 February 2023
Published in:	Transport Reviews 2023, 43(5)
DOI:	https://doi.org/10.1080/01441647.2023.2189323

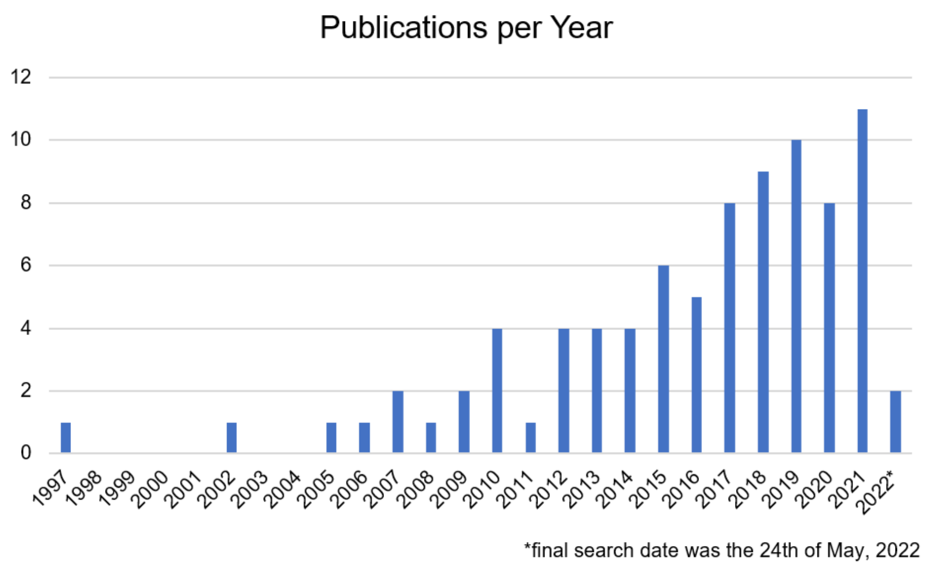


Figure 9: Publications per year on the topic of pedestrian accessibility (Source: Merlin and Jehle (2023))

The first publication presents a systematic scoping review of the academic literature concerning pedestrian accessibility. As visualised in *Figure 9*, the interest in walking accessibility has steadily increased in the last two decades. The transportation component is found to be relatively undeveloped, as pedestrian infrastructure includes many influential elements that are currently not considered. Furthermore, the review confirms that most studies do not account for the significant variation across individual capabilities and preferences regarding walking. Based on the findings, recommendations for future accessibility measures are drawn.

Contribution of the candidate:	Conceptualisation of the research, formal analysis, data visualisation, writing of the paper

Table 4: Overview of Publication 2

Publication 2	**Connecting people and places: Analysis of perceived pedestrian accessibility to railway stations by Bavarian case studies**
Authors:	Ulrike Jehle, Cara Coetzee, Benjamin Büttner, Elias Pajares, Gebhard Wulfhorst
Accepted:	27 May 2022
Published in:	Journal of Urban Mobility 2022, 2, 100025
DOI:	https://doi.org/10.1016/j.urbmob.2022.100025

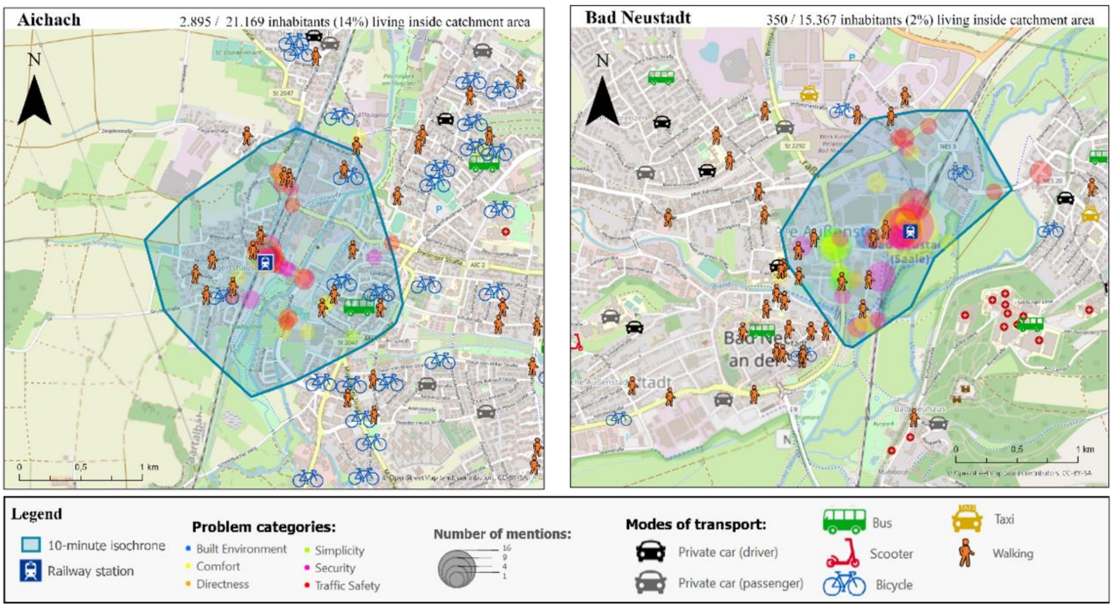


Figure 10: Juxtaposition of calculated accessibility and user statements (Source: Jehle et al. (2022))

The second publication explores the perceived walking accessibility to train stations. On-site and online surveys are conducted in five Bavarian towns (Germany) and the results are statistically analysed. Furthermore, calculated accessibility (10-minute isochrones) is juxtaposed with user perceptions. Results for two sample cities are shown in *Figure 10*. This study confirms that there is a mismatch between calculated and perceived accessibility. Above all, comfort, safety and security factors play an important role for pedestrian accessibility. In addition, significant differences were found between different age groups and city sizes.

Contribution of the candidate:	Survey conduction, formal analysis, data visualisation, writing of the paper

Table 5: Overview of Publication 3

Publication 3	**Analysis of the quality of footpaths to schools: Development of indicators based on OpenData**
Authors:	Ulrike Jehle, Elias Pajares
Accepted:	2021
Published in:	Land Use Monitoring XIII. Land Policy - Concepts Analyses - Tools. IÖR Schriften 79, pp. 221-231.
DOI:	https://doi.org/10.26084/13dfns-p020

Figure 11: Walkability Index (Source: Jehle and Pajares (2021))

The third publication summarises the findings from a literature review on existing walkability measures and presents the development of a new multi-criteria walkability index, WALKIE. It is fed with a large number of open data sets and applied to the City of Freiburg. Therefore, different data platforms are explored and the influencing attributes of walkability are examined. The resulting walkability index is integrated into the planning tool GOAT and shows the walkability per path segment (see *Figure 11*). In addition, an algorithm for calculating pedestrian potential flows is developed to prioritise specific measures for improving walkability. School routes are presented as a sample case study.

Contribution of the candidate:	Conceptualisation of the research, development of methodology, formal analysis, data visualisation, writing of the paper

Table 6: Overview of Publication 4

Publication 4	**How does pedestrian accessibility vary for different people? Development of a Perceived user-specific Accessibility measure for Walking (PAW)**
Authors:	Ulrike Jehle, María Teresa Baquero Larriva, Mahtab BaghaiePoor, Benjamin Büttner
Accepted:	6 August 2024
Published in:	Transportation Research Part A: Policy and Practice 2024, 189, 104203
DOI:	https://doi.org/10.1016/j.tra.2024.104203

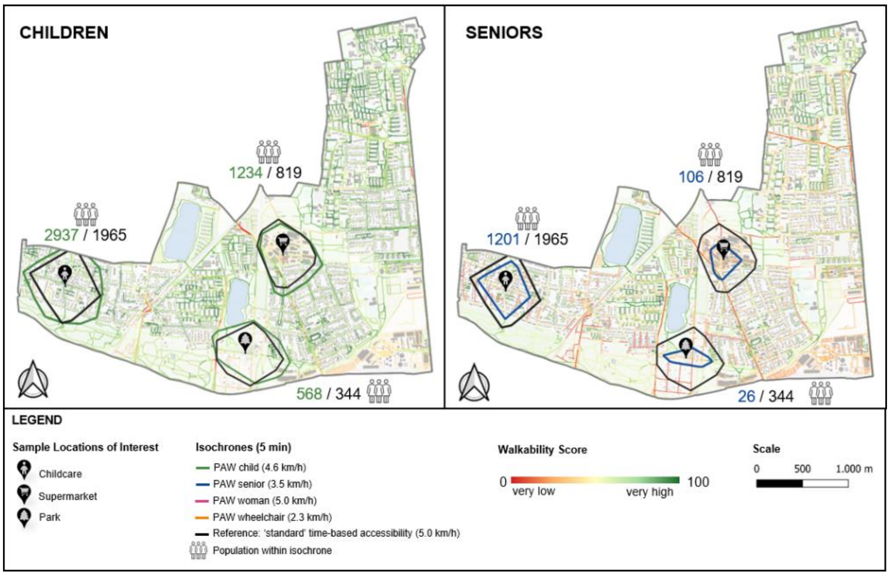


Figure 12: PAW for children and seniors (Source: Jehle et al. (2024))

In the fourth publication, a new accessibility measure, PAW, that considers user-specific perceptions and walkability needs is developed. PAW is applied for four sample user groups: seniors, children, women, and wheelchair users. This is done by working with perceived time and imputing the perceptions. Per user group, the most important walkability attributes are included in the accessibility formula and weighted according to their relevance based on a literature review using the AHP method. Results for a district of Munich (Germany) are visualised (see *Figure* 12) and juxtaposed with a conventional time-based accessibility measure. The results unveil a more nuanced understanding of perceived walking accessibility and its variabilities across different user demographics.

Contribution of the candidate:	Conceptualisation of the research, development of methodology, formal analysis, data visualisation, writing of the paper

Part II

Scientific publications

4. Global interest in walking accessibility: a scoping review

This chapter is an Original Manuscript of an article published by Taylor & Francis Group in Transport Reviews on 27 Feb 2023.

Louis A. Merlin & Ulrike Jehle (2023): Global interest in walking accessibility: a scoping review. Transport Reviews, 43:5, 1021-1054. https://doi.org/10.1080/01441647.2023.2189323.

Both authors contributed equally to this article.

Abstract

We conduct a systematic scoping review of the academic literature concerning pedestrian accessibility. We distinguish "walk accessibility" from the broader topic of "walkability" by two criteria: papers must consider one or more destination type(s), and papers must address the issue of distance or impedance. After searching Web of Science, TRID, and Google Scholar databases and conducting screening, we identify 85 papers meeting these criteria.

We organize the literature review according to the four components of accessibility identified by Geurs and van Wee (2004): 1) Land-use; 2) transport; 3) temporal; and 4) individual and also add a section on the topic of impedance. Walk accessibility studies address a much greater range of land uses or destination types than is typically found for other modes. The transportation component is relatively undeveloped, as pedestrian infrastructure includes many influential elements not currently tracked in GIS systems. Few studies address the temporal component of walk accessibility, which varies according to climatic and nighttime conditions. Most papers do not account for the significant variation across individual capabilities and preferences regarding walking. We note that developing detailed pedestrian networks is a key first step, as most published analysis is conducted on roadway networks. A second major recommendation is to consider individual variations in walk accessibility across demographic classifications, accounting for varying levels of physical mobility.

4.1. Introduction

4.1.1. Background

Understanding pedestrian accessibility is a topic of widespread concern for transport planners and society generally. Walking is the most universal of modes – available for most persons for most of their life span and available across the globe, regardless of a country's level of economic development. In this paper, we include personal transport by wheelchair within the scope of walking, as people traveling by wheelchair usually rely on the same infrastructure as pedestrians in cities and travel at compatible speeds. Walking is an essential component of travel in cities, as other modes – such as driving, transit, or even airplane travel – have a walk-access and a walk-egress component. Scholars and planners who advocate for better transit systems are also concerned with the ability of pedestrians to access transit stops (see for example Bivina, Gupta, and Manoranjan 2020; Jehle et al. 2022; Sarker, Mailer, and Sikder 2019).

Travel by foot is perhaps the most sustainable mode (Jou 2011; Replogle and Fulton 2014). Walking generates no greenhouse gases or other air pollution, and the infrastructure it requires is relatively inexpensive and space-efficient compared to motorized modes. Because people take little space while walking and travel at slow speeds, pedestrians are rarely subject to congestion, only in the most crowded cities. The safety costs of a “crash” between pedestrians are minimal. Walking has significant physical and mental health benefits (Chin et al. 2008; Moniruzzaman, Páez, and Morency 2014; Office of the Surgeon General (US) 2015). From an equity perspective, walking offers mixed benefits: travel by foot is one of the most affordable means of travel, yet the physical capability for walking can vary widely. Hence, destinations that are only accessible by foot may exclude some population segments.

In this paper, we focus on walking accessibility and distinguish it from the more general concern of walkability. Walkability is a broad and, at times, vague concept that can include the enjoyment of pedestrians of a particular facility or place (A. B. Jacobs 1993), the compatibility of an environment with urban design principles (Ewing 1999), or a prediction the amount of walking likely present in a specified area (Frank et al. 2010). Walking accessibility, on the other hand, is tethered to the accessibility concept, which concerns the ability of persons of varying abilities to reach specified destinations (Levine, Grengs, and Merlin 2019). Therefore, our concern here is for utilitarian walking for travel rather than undirected recreational walking or walking for health reasons alone.

Measuring walking accessibility presents various challenges that are not as pronounced for motorized modes. First, pedestrian infrastructure is very fine-grained and rarely recorded at the necessary level of detail to accurately calculate walking accessibility (Iacono, Krizek, and El-Geneidy 2010). Pedestrian infrastructure also plays a more prominent role because pedestrians are more sensitive and vulnerable to environmental conditions, threats, and the hazards of poor infrastructure. Second, the ability of individuals to walk, and their attitudes towards walking, vary greatly. Therefore, much more attention must be paid to the individual component compared to other modes. Generally, the ability of drivers to overcome distance on a particular roadway segment at a particular time of day is assumed to be relatively constant and does not vary by whom is driving. In contrast, walking abilities, needs, and preferences differ highly based on personal characteristics. The same walking infrastructure may be perceived quite differently by different persons. Recent studies (e.g. Gebel et al. 2011; Jehle et al. 2022; Jean Ryan and Pereira 2021) have therefore discovered a mismatch between objective and perceived accessibility and highlighted further research needs to explore this divergence (De Vos et al. 2022).

Walking accessibility has not received as much attention as accessibility by private vehicle or public transit. Nevertheless, our search indicates an accelerating interest in the topic (see *Figure 13*). Our earliest paper is from 1997, but we find more than five (5) papers each year from 2017 to 2021. We attribute this increasing interest to improved utilisation of geographic information systems (GIS), which are an essential instrument for nearly all accessibility studies, and the availability of increasingly detailed data concerning the built environment.

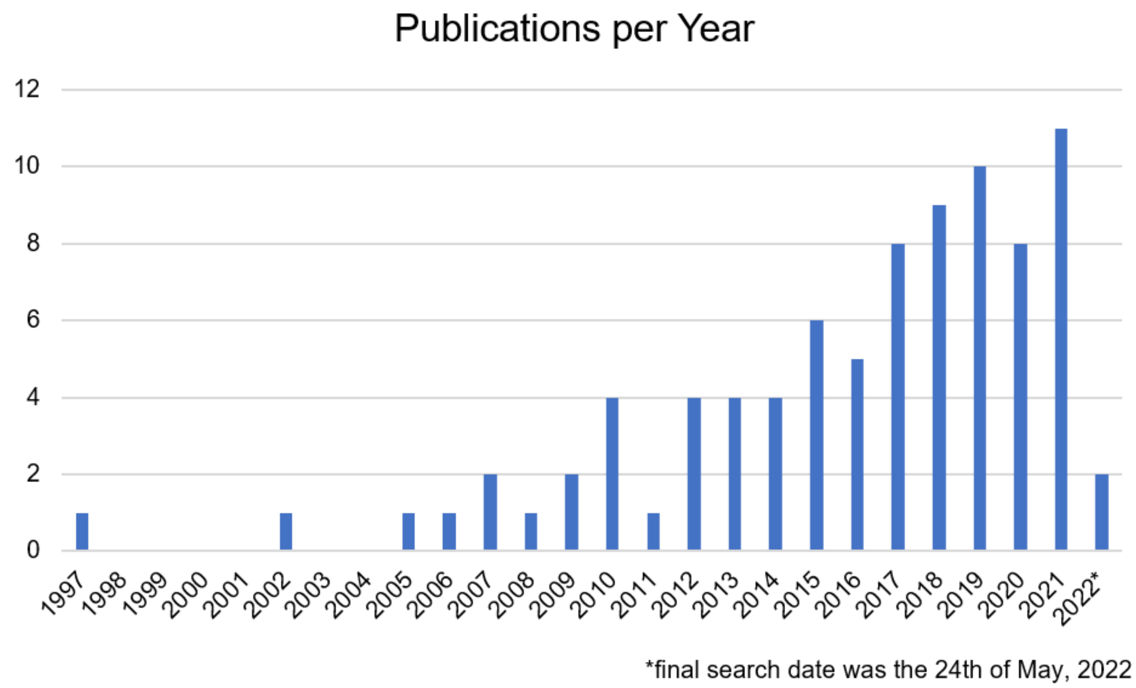


Figure 13: Publication per year on the topic of pedestrian accessibility

4.1.2. Theoretical framework

We employ two key criteria for inclusion in our literature review: the specification of at least one specific destination type and the application of a measure of impedance. These criteria correspond with the two essential elements of accessibility identified by Wu and Levinson (2020) in their paper *Unifying Access*. In this paper, Wu and Levinson (2020) survey the wide number of mathematical formulae for computing accessibility, all of which can be connected to the generalized formula (also adapted from Páez et al. (2010)):

$$\boxed{A_{ik}^{pt} \propto \sum_{j=1}^{J} g\left(O^{t}{}_{jk}\right) f\left(C_{ij}^{p}\right)} \qquad (3)$$

Where A_{ik}^{pt} is an accessibility measure from an origin *i*, at time *t*, to destination type *k*, for person type *p*, $g\left(O^{t}{}_{jk}\right)$ is a measure of the attractiveness of opportunities of type *k* at destination *j* available at time *t*, and $f\left(C_{ij}^{p}\right)$ is a measure of the impedance of travelling from origin *i* to destination *j* for person type *p*. Note that the functional form *f()* concerns an impedance decay function, while C_{ij}^{p} is the generalized travel cost, which may take into account factors such as time, distance, and effort.

Following Geurs and van Wee (2004) we examine each paper along the four components of accessibility measurement: land-use, transport, temporal, and individual. Per Geurs and van Wee:

- The **land-use component** includes the spatial location of origins and destinations, the amount and quality of destinations, and the potential competition for destinations when demand outstrips supply;
- The **transport component** includes transport infrastructure and services and how those translate into a disutility for travel from a particular origin to a particular destination, including factors such as travel time, cost, and effort;
- The **temporal component** incorporates scheduling constraints due to time commitments and scheduling availability;
- And the **individual component** addresses the varying needs, goals, and capabilities across persons, noting that all modes are not equally available.

Our definitions of these components largely conform with the suggestions of Geurs and van Wee (2004) as above. We expand the temporal component to include not only time constraints and the time availability of destinations, but also how nighttime conditions and weather can impinge upon the impedance experienced during pedestrian travel.

Figure 14 illustrates our conceptual framework regarding the four components and how they relate to the opportunities and the impedance articulated in *Equation (3).* The availability and attractiveness of destinations, $g\left(O^{t}{}_{jk}\right)$, is primarily encapsulated by the land-use component – though it could also be influenced by differences between individuals in how they value destination types, and by temporal components concerning when facilities are available.

However, we find that the impedance element of pedestrian accessibility – $f(C_{ij}^{p})$ – is influenced by each of the four components, as well as the interactions between these components. Geurs and van Wee (2004) suggest that the individual component interacts with each of the other components, i.e. "a person's needs and abilities that influence the (valuation of) time, cost and effort of movement, types of relevant activities and the times in which one engages in specific activities". However, we find evidence of interactions across all four components relative to the impedance element. For example, transport and temporal considerations overlap when taking into account how lighting influences the ability to walk at night; land use and temporal considerations interact when accounting for how the value of shade depends upon the prevailing weather; and the land uses present along a segment can influence the disutility experienced, demonstrating an interaction between land use and transportation infrastructure.

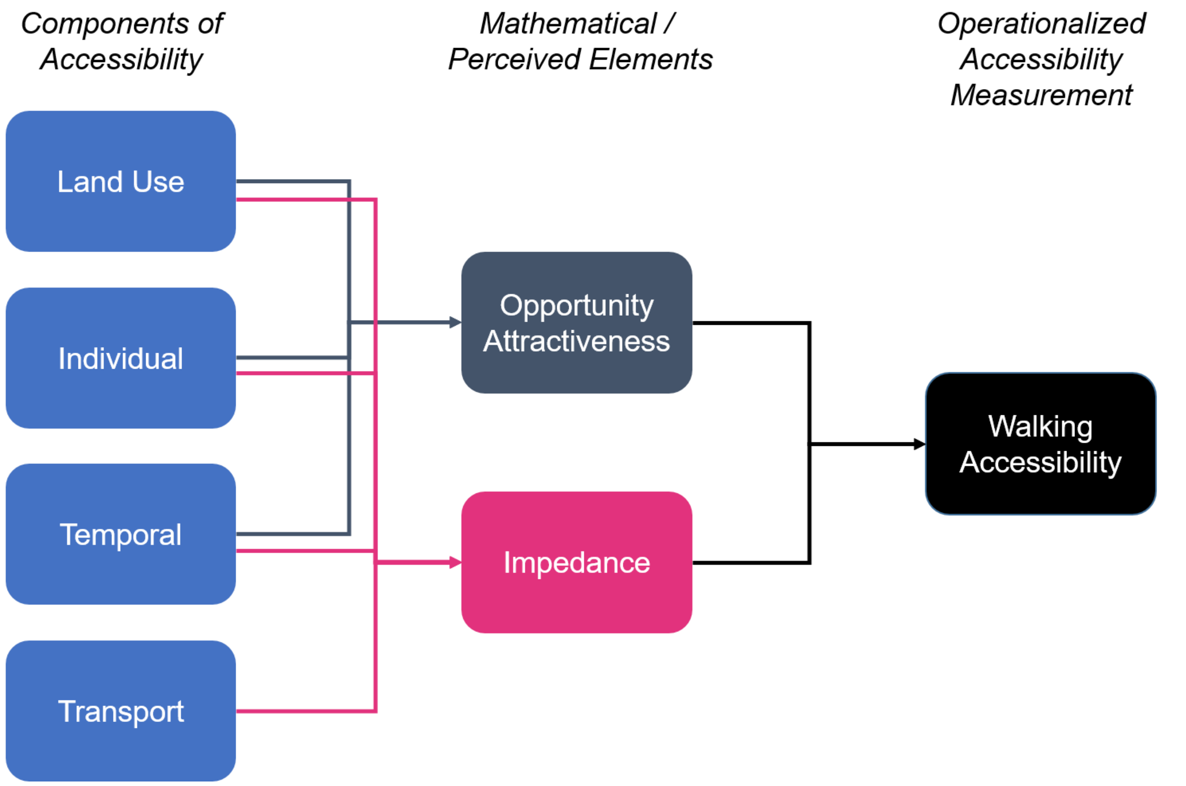


Figure 14: Concept framework

Thus, this *Figure 14* illustrates how each of the four components feeds in turn into the two mathematical elements of destination attractiveness and travel impedance. Our review focuses on this latter aspect – how each of the four components influences travel impedance as experienced by different pedestrians and through their varying perceptions. We acknowledge that more complex conceptual frameworks are viable and may shed light on different issues. For example, the concept framework recently proposed by De Vos et al. (2022) highlights the difference between perceived and objective accessibility, and their potential differential effects on outcomes some as walking behaviour and walking satisfaction. However, in this effort, we focus on the four components outlined by Geurs and van Wee (2004) and how they are differentially operationalized into mathematical formulae for the computation of pedestrian accessibility.

4.1.3. Structure of the paper

The paper proceeds as follows. *Section 4.2* describes our methods for searching for relevant literature, screening, and data collection from each piece of work. In *Section 4.3*, we explore how the body of literature approaches each of the major components of walking accessibility: land use, transportation, individual, and temporal. We note the most common approaches to each component and also discuss novel and promising approaches. Then we discuss how each of these components influences the calculation of impedance, or the second element in *Equation (3).* In *Section 4.4*, we offer a review and recommendations regarding how research and practice concerning walking accessibility might be improved. Following that, we offer a summary of major points in the conclusion (*Section 4.5*).

4.2. Methodology

We conduct a scoping literature review on the topic of walking accessibility. A scoping literature review aims to provide a comprehensive picture of approaches within a given field, with the objective of defining a field's conceptual boundaries (Xiao and Watson 2019). This approach helps to identify the strengths and weaknesses of existing research approaches and identify research gaps. In the first stage, we searched the literature with three research databases: Web of Science, Google Scholar, and the TRID database provided by the Transportation Research Board (final search date: 24th of May, 2022). Within each of these databases, we look for at least one title term related to walking, including "pedestrian", "walk", "nonmotorized", and "non-motorized" as well as one title term related to accessibility, for which we solely relied upon the term "accessibility". We also conducted searches with the term "access" but found too many results to be meaningfully reviewed. Within Web of Science, we found 112 unique articles; in TRID, 63; and in Google Scholar, we limited the search to the topic "pedestrian accessibility" and the results to the first 100 as listed by relevance. After combining the results of the three searches, we netted 181 articles from the raw literature search (see *Table 7*). In the few cases where articles were unavailable from online databases, we emailed authors requesting a copy.

Table 7: Summary of paper identification search

Database	Title Search	Number of Results	
Web of Science Core Collection	“nonmotorized” and “accessibility”	2	Σ 112
	“non-motorized” and “accessibility”	8	
	“walk” and “accessibility”	53	
	“pedestrian” and “accessibility”	52	
TRID	“nonmotorized” and “accessibility”	3	Σ 62
	“non-motorized” and “accessibility”	7	
	“walk” and “accessibility”	12	
	“pedestrian” and “accessibility”	51	
Google Scholar	Topic Search: “pedestrian accessibility” limited to top 100 results by relevancy	56	Σ 56
Total		Σ 230	
Duplicates Removed		49	
		Σ 181	

In the next stage, we screened the articles by reviewing their titles and abstracts. Our inclusion criteria were: (1) The article must be in English; (2) the primary mode of travel analysed must be walking; (3) the paper must discuss walking to destinations; and (4) the article must discuss some measure of distance, cost, or impedance. We opted for inclusion in those cases where we were uncertain about whether an article met these criteria. After screening, 82 articles remained. During our review process, we came across three (3) additional articles meeting our criteria, resulting in a total of 85 articles reviewed. For the purposes of data extraction, we identified the following fields of interest: Study title, journal of publication, study area (city or metro), study continent, measurement of impedance or distance, land-use component (origins, and destinations), transport component (pedestrian network), inclusion of an individual component, inclusion of a temporal component, if the study was on perceived or objective accessibility, analysis method, results, innovative features, and limitations. Only one member from the research team reviewed each paper. We did an initial pass reviewing eight (8) papers together and discussing our findings to synchronise our understanding of key concepts and data extraction methods. A condensed summary of the data extraction is available in the *Appendix*. The vetted papers represent a genuinely global geography, as indicated in *Figure 15*. Though European and North American publications are most numerous, every continent besides Antarctica is represented. The fields of study housing publications concerning walking accessibility are also diverse. While 35 publications are from transport-related journals, there are also 11 from general planning, 11 from geography and GIS, five from health-related journals, and four from computer science journals or conferences (note that these counts are not mutually exclusive).

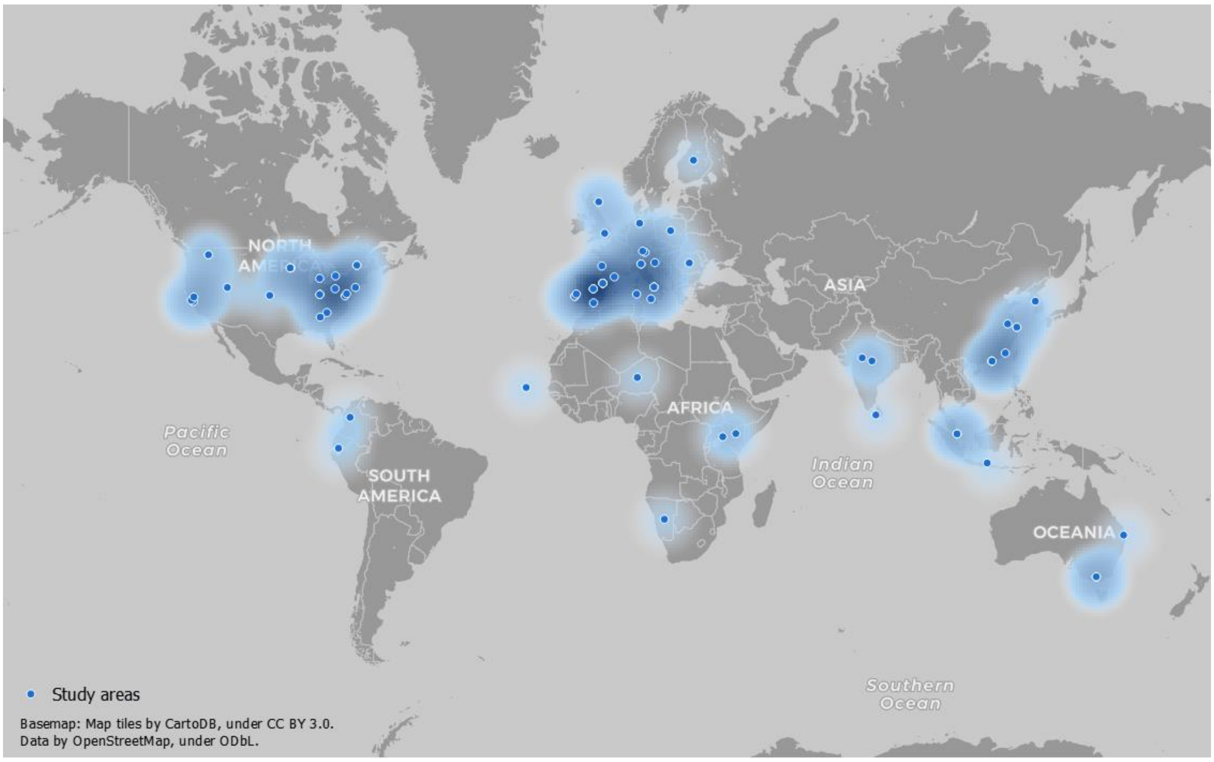


Figure 15: Map of study area locations

4.3. Literature review findings

In this section, we are discussing the findings from the literature review. It is divided into six subsections (transport component, land-use component, individual component, temporal component, impedance calculation, and objective vs. perceived accessibility). In each of them, first a general overview of the most common practice is given, followed by a deeper dive into some exceptional examples.

4.3.1. Transport component

The first step in computing pedestrian accessibility is to build a pedestrian network. Analysts often accomplish this by starting with the road network and subtracting out roads that do not accommodate pedestrians (Carpio-Pinedo, Benito-Moreno, and Lamíquiz-Daudén 2021; Roblot et al. 2021; Vale and Pereira 2017). OpenStreetMap (OSM), the open, crowdsourced geographic database, is freely available and offers global coverage and so can be an appropriate starting point for streets (Liu et al. 2021; Pearce, Matsunaka, and Oba 2021; Tiran, Lakner, and Drobne 2019). However, many attributes that are important for pedestrians (such as sidewalk availability, width, lit, and surface) are often not complete within OSM. In a few cases, researchers have gone to significant trouble to build accurate pedestrian networks far beyond the roadway network (Amaya et al. 2022; D'Orso and Migliore 2018; Erath et al. 2017; Jonietz and Timpf 2012; Pearce, Matsunaka, and Oba 2021; Sinagra 2019; Sun et al. 2015; Tang et al. 2021). *Figure 16* provides an overview of features and their corresponding measurements that could be considered in calculating accessibility. The large number of potentially relevant items illustrates the difficulty of collecting comprehensive pedestrian network data.

Pathway	Surrounding Environment	Crossings	Obstacles	Operational Characteristics
Cross Slope	Land Cover	Curb Ramps (For wheelchairs, etc.)	Electric and Utility Poles	Pedestrian Flow Rate
Footpath Availability	Illuminance	Crosswalk Presence and Type	Gates/Fences	Vehicle Speeds
Footpath Slope	Intersecting Driveways	Medians	Grates	Illuminance
Footpath Width	Number of Adjoining Traffic Lanes	Pedestrian Crossing Signal	Other Obstacles	
Surface Material	Number of Points-of-Interests (POIs) along the path	Signalized Intersection		
Surface Smoothness	Presence of Benches			
Presence of Gaps, Dips, or Height Changes	Presence of On-Street Parking			
	Presence of Vegetation			
	Spatial Separation from Bicycles			
	Spatial Separation from Vehicles			
	Shelter, Shade, or Cover			

Figure 16: Potential measurable characteristics of pedestrian links

Accurate pedestrian networks are a substantial challenge to build, both because local authorities often do not collect thorough pedestrian data and because many environmental features can affect the pedestrian experience (Parmenter et al. 2008). Pedestrian networks can include not only sidewalks but also plazas, parks, shared-use paths, pedestrian bridges and underpasses, off-street paths, stairways, escalators, street crossings, interior corridors, and building entrance locations. Relevant data on the individual segments may include surface, evenness, slope, obstacles, width, greenery, presence of certain land use activities, and more (Alfonzo 2005; Lo 2009; Wimbardana, Tarigan, and Sagala 2018). Laakso et al. (2013) propose a comprehensive information model for capturing data regarding pedestrian accessibility and pedestrian routing. They capture a variety of pedestrian pathway types (including crossings) through linear features classified as "PedestrianPassage" and a range of obstacle types through primarily point features classified as "PedestrianObstacle". Li et al. (2018) propose a streamlined method for developing a sidewalk and crosswalk network where none exists, building upon existing parcel and roadway network GIS files. The method is semi-automated, but some hands-on data cleaning is required.

Van Eggermond and Erath (2016) developed two contrasting pedestrian networks for Singapore and examine accessibility differences across these two networks. The first network is simply a network of applicable roadway centre lines. For the second network, they developed sidewalks for both sides of the street by using an offset from roadway centrelines. They also identified three types of roadway crossings: overhead bridges, pedestrian underpasses, and painted crosswalks. They find that detailed pedestrian networks more accurately capture pedestrian accessibility, but a substantial amount of ground truthing is required to develop correct networks. Several other researchers use site visits, Google Street view, or aerial maps to construct detailed pedestrian networks (Achuthan, Titheridge, and Mackett 2007; Amaya et al. 2022; Blečić et al. 2013; D'Orso and Migliore 2018; Jonietz and Timpf 2012; Laakso et al. 2013; Pearce et al. 2021; Sinagra 2019; Stewart 2016; Tang et al. 2021; Wilhelm 2007; Xu 2014).

Adding off-street pedestrian network features, such as shared-use paths, is also relevant; these features are usually not captured in roadway networks. Off-street pedestrian networks, when they provide additional options beyond the street-based network, can result in shorter paths and improved accessibility (Tal and Handy 2012). Shared use paths may also be preferred routes for reasons of safety and aesthetics (Erath et al. 2015).

The infrastructure element of accessibility is interwoven with the individual element; depending upon which population segments researchers are considering, their data collection needs may differ. In particular, when considering the accessibility needs of persons in wheelchairs or with constrained mobility, obstacles and surface unevenness become more severe constraints (Laakso, Sarjakoski, and Sarjakoski 2011; Laakso et al. 2013; Orellana et al. 2020; Sinagra 2019; Wilhelm 2007). To capture the needs of these populations, investigators must detail features such as physical obstacles present in the pedestrian pathway, curb ramps, driveway ramps, textural changes (for the visually impaired), roughness, cross slope, tripping hazards, and dips. Likewise, Amaya et al. (2022) consider the presence of benches when evaluating walking accessibility for older adults.

Although the overwhelming majority of papers investigating walking accessibility employ a graph-based model of pedestrian infrastructure (where the pedestrian network consists of nodes and edges connecting them), there are exceptions. For example, Blanford et al. (2012) consider walking accessibility to health care facilities in Niger in rural areas where road networks may be lacking. Therefore, they consider raster-based routing that considers elevation and land cover as potential pedestrian obstacles that increase impedance. Páez et al. (2020) perform a similar analysis in Kenya while examining residents' access to water, primarily considering the distance and slope of alternative raster-based routes. Rossetti et al. (2020) also employ a raster-based approach, this time in urban Italy. Their reasoning for employing a rasterized method is that pedestrian routing through parks and plazas involves a high degree of discretion and cannot readily be simplified into a discrete set of possible linear pathways. Raster-based routing methods offer an appealing alternative when formal pedestrian infrastructure is absent but involves much more computational load than a network approach, so its applicability is likely of limited use.

4.3.2. Land-use component

Land use features in the consideration of pedestrian accessibility in three ways: as origins, as destinations, and as a feature of segments alongside pedestrian routes. Reviewed papers most commonly consider residences as the primary origin of interest, i.e. walk trips starting from home, for 32 out of the 85 papers. Several papers consider any possible location in the city as an origin (Ariza-Álvarez, Arranz-López, and Soria-Lara 2021; Liu et al. 2021; Roblot et al. 2021) or consider any building as an origin (Erath et al. 2017; Higgins, Nel, and Bruyns 2019; Sun et al. 2015). This finer building-scale analysis is relevant when considering walking accessibility, where even building location entrances and under- or overpasses can be accounted for (Desjardins, Higgins, and Páez 2022; Tang et al. 2021). Several papers consider public transport stops (Chandra, Jimenez, and Radhakrishnan 2017) or parking lots (Jonietz and Timpf 2012) as origins. Destinations are notably more diverse than in the study of transit and auto accessibility, where most studies focus on accessibility to jobs. Destination types considered include jobs, parks and green space, health service facilities, schools, childcare facilities, shopping centres, and transit stops. The categorisation and nomenclature of destinations are not standardized, and different papers employ differing terminologies for what appear to be the same concepts, i.e. “commercial areas” versus “shopping” versus “services”. The most common destinations analysed are a variety of points of interest (23/85), parks and recreational amenities (13/85), transit stops (11/85), and shopping (10/85). Land uses occurring along pedestrian segments can influence perceived impedance, though few reviewed studies examine this. Van Eggermond and Erath (2016) and Erath et al. (2017) employ a stated preference survey to determine that pedestrians in Singapore prefer to walk along segments with greenery and with shops. Likewise, Broach and Dill (2016) found that perceived impedance is lower along main streets (commercial streets) in Portland, Oregon, via a revealed preference survey using GPS. Several other papers consider the effect of greenery or commercial activity on pedestrian impedance (Blečić et al. 2015; D’Orso and Migliore 2018; Gaglione, Cottrill, and Gargiulo 2021).

4.3.3. Individual component

While most papers that we reviewed do not distinguish between different populations, there is a rich and growing literature on the individualized aspects of walking accessibility. Researchers considered the demographic components of age, gender, income, health, mobility constraints, vision constraints, vehicle ownership, and more in the papers we reviewed. There are two distinct approaches to examining individual differences. One approach is to identify population segments with distinctive characteristics and consider their particular needs (Orellana et al. 2020; Papa, Carpentieri, and Guida 2018; Wilhelm 2007). The second approach is to integrate multiple population characteristics into a statistical formula for fully individualized accessibility profiles (García-Palomares, Gutiérrez, and Cardozo 2013; Marquet and Miralles-Guasch 2014; Reyes, Páez, and Morency 2014).

Several of the reviewed papers examine walking accessibility for older adults (Amaya et al. 2022; Ariza-Álvarez, Arranz-López, and Soria-Lara 2021; Boakye-Dankwa et al. 2019; Borowska-Stefańska and Wiśniewski 2017; Cheng et al. 2019; Colclough 2009; Erath et al. 2015; Gaglione, Gargiulo, and Zucaro 2019; Gaglione, Cottrill, and Gargiulo 2021; García-Palomares, Gutiérrez, and Cardozo 2013; Marquet, Bedoya, and Miralles-Guasch 2017; Pajares et al. 2021; Papa, Carpentieri, and Guida 2018; van der Vlugt, Curl, and Scheiner 2022). Gaglione, Cottrill, and Gargiulo (2021) examine pedestrian access of older adults to urban services in Naples, Italy, and Aberdeen, Scotland, by utilising a value of perceived travel time that considers the traveller’s age. They aim to identify areas of the pedestrian network where interventions could increase senior access. Jehle (2020) examines how elderly accessibility varies from a “standard” pedestrian profile in Munich using the open-source software tool GOAT. Using differential speeds across traveller types, they find a much lower level of walking accessibility among the elderly. Cheng et al. (2019) calculate cumulative opportunity accessibility measures with varying distance thresholds based upon multiple individual and household level characteristics, including age. Therefore, the level of accessibility depends not just upon location and infrastructure but also on individual social and demographic characteristics. They find that older adults have lower access to recreational facilities than their younger counterparts.

Surprisingly, walking accessibility for children was much less frequently analysed in our set of papers. Reyes, Páez, and Morency (2014) examine children’s walk accessibility to urban parks in Montreal employing a spatial expansion model. García-Palomares, Gutiérrez, and Cardozo (2013) consider the accessibility of different population groups to metro stations and incorporate children within their analysis. But few reviewed papers consider children’s walking access, despite the unique needs of this group, and children’s greater dependence on walking as a mode of transport.

Wheelchair users have distinctive needs regarding pedestrian infrastructure, so several researchers have delved into methods for accurately assessing their accessibility (Church and Marston 2003; Jehle 2020; Laakso, Sarjakoski, and Sarjakoski 2011; Laakso et al. 2013; Orellana et al. 2020; Sinagra 2019; Wilhelm 2007). Detailed data sets are necessary that include the collection of curb ramps, driveway ramps, sidewalk texture, obstacles, and slope

(Jehle 2020; Laakso, Sarjakoski, and Sarjakoski 2011; Laakso et al. 2013; Orellana et al. 2020; Sinagra 2019; Wilhelm 2007). Some of these features can present absolute obstacles to wheelchair travel, while others represent an impediment that makes wheelchair travel more burdensome, creating a higher impedance (Sinagra 2019; Wilhelm 2007).

Socioeconomic variables, such as income, vehicle ownership, and housing type, are also sometimes used to evaluate differences in pedestrian accessibility (Anciaes, Nascimento, and Silva 2015; Ariza-Álvarez, Arranz-López, and Soria-Lara 2021; Boakye-Dankwa et al. 2019; Chandra, Jimenez, and Radhakrishnan 2017; Cheng et al. 2019; Damurski, Pluta, and Zipser 2020; García-Palomares, Gutiérrez, and Cardozo 2013; Goodwin 2005; Higgins, Nel, and Bruyns 2019; Marquet, Bedoya, and Miralles-Guasch 2017; Morar, Radoslav, and Spiridon 2014; Reyes, Páez, and Morency 2014; van der Vlugt, Curl, and Scheiner 2022; Xu 2014). Ariza-Álvarez, Arranz-López, and Soria-Lara (2021) calibrate different gravity decay functions based on various socioeconomic characteristics, including income and vehicle availability. Marquet, Bedoya, and Miralles-Guasch (2017) consider which population segments are most likely to take shorter "proximity trips" to understand what groups would most value local accessibility. They find that age, gender, and economic status are correlated with the likelihood of taking proximity trips. Socioeconomic variables may help analysts identify accessibility differences across populations as well as observed differences in the likelihood of overcoming a particular distance.

4.3.4. Temporal component

Relative to the land-use and transport components of walking accessibility, the temporal component is relatively less studied. Only nine of the reviewed papers consider the effect of nighttime (Chandra, Jimenez, and Radhakrishnan 2017; Jehle 2020) or variations in weather (Erath et al. 2015) on pedestrian accessibility. Erath et al. (2015) note that shaded and covered routes are preferred in hot, sunny Singapore and that the value of covered routes increases during rainfall events. Jehle (2020) examine how accessibility to POIs varies based on the opening hours each POI is available.

4.3.5. Impedance calculation

Each of the accessibility components – transport, land-use, individual, and temporal – can have an independent or combined effect on the calculation of impedance along a given route. Transportation infrastructure defines which routes are shorter as well as the relative difficulty of traversing each route. Land use determines the location of origins and destinations, their quality, and whether or not there are interesting diversions along the route for pedestrians. The individual component defines each person's physical ability to overcome spatial separation and their variable degree of sensitivity to infrastructure conditions. The temporal component – through reduced illumination or weather – can also serve to increase impedance or effectively remove specific unilluminated travel paths from the network.

Despite these manifold possibilities, the most common approach in the literature to calculating impedance is simply distance, which was employed in 25 out of the 85 papers reviewed, with modified versions of distance employed in an additional 11. In almost all cases, analysts used pedestrian network distance, not straight-line distance. Researchers often applied cumulative opportunity measures and distance-decay measures of route distance to destinations. In some cases, distances were modified by considering aspects of transportation infrastructure that increased "effective" distance, such as slope (Blečić et al. 2013; 2015; Blečić, Cecchini, and Trunfio 2018; D'Orso and Migliore 2018; Kuzmyak, Baber, and Savory 2006). Others tried to incorporate perceived distance by adding impedances based on the quality of the path, assigning greater lengths to unpleasant routes (Blečić et al. 2015; Blečić, Cecchini, and Trunfio 2018; D'Orso and Migliore 2018; Jang et al. 2020; Jonietz and Timpf 2012).

The second most common method for measuring impedance was travel time, which was employed in 31 out of 85 papers. Travel time can be translated to distance if an expected walking speed is assumed; however, different individuals walk at different speeds (and with differing levels of physical effort). Several analyses account for differing travel speeds across population segments (Amaya et al. 2022; Gaglione, Cottrill, and Gargiulo 2021; Jehle 2020). Interestingly, some research indicates that people better estimate walk times than walk distances (Vale and Pereira 2017). Travel time can also be adapted to account for infrastructure characteristics, therefore increasing the walk time along any particular segment due to slope or impediments (Amaya et al. 2022; Gaglione, Cottrill, and Gargiulo 2021; Hanyan Li et al. 2018; Tang et al. 2021; Wilhelm 2007). Lastly, several investigations examine perceived travel time as an impedance measure by asking travellers about their perceptions or willingness to travel along specific routes based on each route's characteristics or attractiveness (Boakye-Dankwa et al. 2019; Erath et al. 2017; Gaglione, Cottrill, and Gargiulo 2021; Sun et al. 2015).

There are several ways to account for perceived travel time. Four methods we identified are: 1) Based upon revealed route-choice behavior (Broach and Dill 2016), 2) Based upon stated preference surveys (Erath et al. 2015), 3) Based upon survey questions to study participants about perceived travel time (Sun et al. 2015), or 4) Based upon assumptions about perceived travel time (Gaglione, Cottrill, and Gargiulo 2021). For example, Boakye-Dankwa et al. (2019) analyzed the connection between perceived accessibility to destinations at different distances from home and self-reported amounts of walking for different purposes among older adults in

Brisbane and Hong Kong. Their survey found that higher perceived destination accessibility was positively associated with the likelihood of walking only in Brisbane. Differing results across the two study cities suggest that local contexts may affect how accessibility is experienced. Sun et al. (2015) investigate the differences between actual and perceived travel time for various routes within a Hong Kong-based campus that includes significant elevation changes. They hypothesize that perceived walking time is primarily a function of distance and elevation change and calibrate a regression of perceived walking time to these variables. Pot, van Wee, and Tillema (2021) consider perceived accessibility to be its own category of accessibility measurement and relate it to the other traditional accessibility components.

Páez et al. (2020) employ a distinctive method for calculating pedestrian impedance, estimating the metabolic energy expended in pedestrian travel across varying routes. Biologically, it is intuitive that humans would endeavor to economize on metabolic energy expenditure while walking. Páez et al.'s (2020) method is also appropriate because of the study context – a rural part of Kenya with few roadways present. Therefore, most pedestrian paths traverse an unpaved landscape, and the metabolic energy expended can vary based upon the landcover and slope. They find that the shortest paths as determined by metabolic energy expenditure are rather different from those that minimize either time or distance.

4.3.6. Objective vs. perceived accessibility

Accessibility studies can be divided in two approaches: *objective* and *perceived* analysis. Objective analyses calculate accessibility using spatial data, while perceived analysis are based on survey or reported data. The majority of the accessibility studies we reviewed used an objective approach. Six papers were identified which used a perceived approach (Abrahams 2010; Arranz-López, Soria-Lara, and Ariza-Álvarez 2021; Boakye-Dankwa et al. 2019; Erath et al. 2015; Iacono, Krizek, and El-Geneidy 2008; van der Vlugt, Curl, and Scheiner 2022). Boakye-Dankwa et al. (2019), Erath et al. (2015), Iacono, Krizek, and El-Geneidy (2008), and van der Vlugt, Curl, and Scheiner (2022) leveraged survey data to analyze perceived accessibility, while Abrahams (2010) conducted face-to-face interviews with selected experts and incorporated passive field observations. The study by Arranz-López, Soria-Lara, and Ariza-Álvarez (2021) compared differing visualizations of accessibility in terms of their comprehensibility.

Eleven studies combined objective and perceived methods (Adams 2002; Arranz-López et al. 2017; Arranz-López, Soria-Lara, and Pueyo-Campos 2019; Arranz-López et al. 2019; Damurski, Pluta, and Zipser 2020; Erath et al. 2017; García-Palomares, Gutiérrez, and Cardozo 2013; Iacono, Krizek, and El-Geneidy 2010; Kang 2015; Reyes, Páez, and Morency

2014; Sun et al. 2015). Arranz-López et al. (2017) and Arranz-López, Soria-Lara, and Pueyo-Campos (2019) survey residents to define different distance-decay functions across user groups; Iacono, Krizek, and El-Geneidy (2010) do the same for different trip purposes. Damurski, Pluta, and Zipser (2020) compare objective and perceived accessibility and find disparities across the two measures. Kang (2015) juxtaposed pedestrian volumes with accessibility values and found that the land use present along pathways impacts the level of walking activity. To account for environmental perceptions, path characteristics and destination attractiveness, Erath et al. (2017) employ behavioral data from surveys to calibrate accessibility indicators. Sun et al. (2015) used the walking diary of 169 students to derive perceptions of walking uphill and incorporate them into a 3D walking accessibility model. Some authors (e.g. Blečić et al. 2013; Blečić, Cecchini, and Trunfio 2018; D'Orso and Migliore 2018; Jonietz and Timpf 2012; Amaya et al. 2022) include walkability attributes in the impedance function, hoping to impute their impact on perceived impedance.

Throughout the papers, different terms are used for perceived accessibility. Most of the authors (e.g. van der Vlugt, Curl, and Scheiner 2022; Boakye-Dankwa et al. 2019) use the term *perceived accessibility* and the term *objective accessibility* as its counterpart. Damurski, Pluta, and Zipser (2020) write *subjective accessibility* and Arranz-López, Soria-Lara, and Ariza-Álvarez (2021) speak of *relative accessibility*, which is explained to be "subjective and shaped by individual circumstances (e.g., individual preferences, habits, and cultural norms)".

4.4. Discussion and recommendations

Our recommendations for research and practice are summarized in *Table 8*, which we discuss in this section. The column indicating current practice describes the most common or modal practice from the body of literature we reviewed; the second column or recommended practice briefly describes our recommendations for future walking accessibility studies.

The first step to improved analysis of pedestrian accessibility is to shift from the use of roadway networks to pedestrian networks. As noted above, the quality of the pedestrian network can vary widely, and detailed and precise data on the pedestrian network is a necessary precondition for accurately analyzing pedestrian accessibility. Fortunately, several researchers have developed thorough data models for capturing the necessary information (Laakso et al. 2013; Sinagra 2019; Xu 2014). Although few jurisdictions have accurate and detailed pedestrian network data, we argue that the time for both researchers and practitioners to start building such networks is now.

Table 8: Current vs. recommended practice for analyzing pedestrian accessibility

Component	Current practice	Recommended practice
Transport	Roadway Network	Pedestrian Network, including Street Crossings
Land-Use	Administrative Zones as Origins / Specific Destination Types	Buildings as Origins or Grid-Type Zones as Origins/ Specific Destination Types
Individual	All Persons the Same	Distinct Population Segments
Temporal	Not Considered	Consider the Effect of Weather and Nighttime
Impedance	Distance	Time
Objective vs. Perceived	Objective	Imputed Perception

One of the most critical features of the pedestrian network that is currently often missing is street crossings. Street crossings may pose either a minor or major obstacle to pedestrian travel (Anciaes and Jones 2020; Broach and Dill 2016; Erath et al. 2015; Montgomery County Planning Department 2020). In most analyses based on the roadway networks, pedestrian crossings are not considered. Factors that may influence pedestrians' ability to cross include the number of traffic lanes, the presence of a median island, prevailing vehicular speeds, the presence of a crosswalk, the presence of a signalized traffic light, and the presence of an overpass or underpass (Anciaes and Jones 2020; Montgomery County Planning Department 2020).

The current dominant practice is to employ existing administrative zones as origins. However, as more detailed GIS data becomes available, it may be possible to use individual buildings as origins, especially major residential complexes with many housing units. Pedestrian travel can vary significantly on the microscale in places where blocks are long or street crossings are infrequent, so the use of individual buildings as origins and destinations is desirable. On the other hand, it may still be preferable to conduct a zonal analysis if the study area is extensive or for the analysis is of an area with many single-family homes. Another reason to prefer zonal analysis is for rapid, sketch-planning type tools (Pajares et al. 2021). A middle route is to create a regular grid of small zones and to interpolate the population to that grid (Desjardins, Higgins, and Páez 2022; Liu et al. 2021).

In the research world, the current modal practice for understanding walking accessibility already considers specific destination types. For example, parks, grocery stores, and schools have all been analyzed as potential walk destinations. We recommend that the disaggregation of destination types be the standard and that this approach also be adopted by those analyzing pedestrian accessibility in practice. Each destination type may have distinct demographic segments that it attracts; distinct patterns in hours of activity; and even differential ability to attract pedestrian trips; therefore, we argue against the aggregation of various destinations into an overall walkability index. As increasingly accurate and detailed information becomes available for POIs, such disaggregated analysis by destination type should become more achievable. In addition, such analyses could take into account the quality of destinations where adequate data is available.

As we have documented here, there is growing attention to the individual aspect of walking accessibility; however, the norm in the literature is still to consider the entire population as experiencing the same opportunity for walking to destinations. We recommend the consideration of different population segments, especially concerning their differential ability to overcome distance, cross streets, and access POIs. The population segments that appear to need attention the most would be older adults, children, those using human-powered wheels (including persons in wheelchairs and persons pushing strollers), and persons with other mobility impairments, i.e., cane users. Each group has specific needs and requirements for walking infrastructure in terms of safety, freedom from barriers, etc. Considering that metabolic energy may be an appropriate way to measure pedestrian impedance, there may be cases where the pedestrian accessibility needs of the overweight and the obese could also be considered in a differential fashion. Still another option that accounts for individual differentiation would be comfort-based accessibility measures that include perceived route attractiveness factors.

However, we do not recommend a fully individualized approach to accessibility, where multiple characteristics of each individual are integrated into a customized accessibility profile. We argue against this for primarily practical reasons. The state of knowledge is not sufficiently developed to make such individualized measures accurate. Moreover, decision makers plan the built environment for general populations, not specific individuals. Individualized accessibility measures complicate identifying significant variations across major population segments. However, analyses disaggregated by population groups (e.g., children's accessibility to kindergartens and primary schools with particular emphasis on the safety of street crossings) may be beneficial to planners to highlight shortcomings in the walking network to essential amenities.

As noted previously, the temporal component is neglected in research and in practice. Despite this, there is evidence that heat, cold, and rain may significantly affect the willingness of persons to walk and may influence the distance they are willing to walk (Merlin et al. 2021). In addition, intuition tells us that walking at night differs from walking during the day and presents unique challenges (Chandra, Jimenez, and Radhakrishnan 2017; Jehle 2020). Since little data has been gathered on this topic, the temporal component of walking accessibility may be more suitable for researchers than practitioners at this time. However, in challenging environments, practitioners should undoubtedly consider designs that mitigate extreme weather (Erath et al. 2017).

The most common unit of impedance measurement for pedestrian accessibility is distance. Distance has several advantages – it is easy to conceptualize and map for planning purposes. Moreover, distance can be adapted to consider each of the accessibility components – for example, expanding the distance when someone is walking upslope or contracting it when someone is walking by a park. However, travel time may be a more advantageous unit of analysis. Firstly, there is evidence that people report time more accurately than distance (Vale and Pereira 2017). Secondly, different accessibility analyses can easily be adapted to different populations by incorporating their variability in walking speeds. Lastly, street crossing time can be added to route times as a rough way to account for the additional impedance created by street crossings.

Most of the reviewed studies focus on objective accessibility. The advantage of objective analyses is that these measures can readily be transferred worldwide if the corresponding spatial data is available. However, in doing so, they neglect variations in perception, which may vary systematically not only across individuals but also across cultures (Golan et al. 2019). Perceived measures, on the other hand, are based on questionnaires conducted for the respective study area and thus the results are not per se transferable. Similar to (Damurski, Pluta, and Zipser 2020), several studies have discovered a mismatch between objective and perceived accessibility (Curl, Nelson, and Anable 2015; Gebel et al. 2011; Lättman, Olsson, and Friman 2018; McCormack et al. 2008; Pot, van Wee, and Tillema 2021; J. Ryan and Pereira 2021; M. Ryan et al. 2016; van der Vlugt, Curl, and Scheiner 2022). In order to obtain realistic and holistic results, we recommend imputing perceived accessibility based on empirical evidence from appropriate studies - thus using the advantages of both approaches.

Finally, we also want to argue not to make the perfect the enemy of the good. While the characteristics outlined in *Table 8* are desirable, they may not be necessary or appropriate in every context. We would rather see more frequent pedestrian accessibility analysis even if it does not meet all of our recommended criteria in *Table 8*. Rather, it is intended to be a guide for the general direction of improvement in pedestrian accessibility analyses.

Our study has several limitations. We only examined three databases and only included papers published in English; in fact, we found several relevant papers published in other languages. Also, we did not receive papers from all authors upon request. It is possible that some highly relevant papers were omitted from our review. Each paper was only reviewed by a single member of the research team; double reviews could improve data extraction. However, given the inclusiveness of our search, we believe we have drawn an accurate picture of the current state of pedestrian accessibility analysis.

4.5. Conclusion

In this paper, we review the global, multidisciplinary literature on pedestrian accessibility, surveying 85 publications. We differentiate the literature concerning pedestrian accessibility from the broader literature on walkability by screening out papers that do not concern reaching destinations or do not incorporate some measure of impedance or distance. This distinguishes our review from a previous effort that did not limit their scope to walking to destinations (Vale, Saraiva, and Pereira 2016). For the purposes of data extraction, we gathered data on the following topics of interest: Study title, publication journal, study area, study continent, measurement of impedance or distance, origins, destinations, method of developing the pedestrian network, variation by population group, temporal considerations, analysis or calculation method, results, innovative features, and limitations.

In order to structure our critique of this body of literature, we employ the framework proposed by Geurs and van Wee (2004), which identifies four components of the accessibility concept: transportation, land-use, individual and temporal. We conceive of these four components, in turn, influencing the two elements of the generalized equation for accessibility from Wu and Levinson (2020) (*Equation (3)*), an element calculating attractiveness and an element calculating impedance or cost (see *Figure 14*). Our analysis indicates that all four components, as well as interactions between the four components, can influence the calculation of impedance.

Based upon the content of our review, we issue several recommendations for research and practice concerning the study of walking accessibility, summarized in *Table 8*. We recommend that, when possible, analysts use pedestrian networks that account for street crossings and other distinctive features of the pedestrian environment rather than relying solely upon roadway networks. Because of the importance of small-scale features of the pedestrian environment to impedance, we recommend that building-level accessibility measures be calculated when feasible. Concerning the individual component of accessibility, pedestrians are subject to much more significant variation than motorized modes, and therefore we argue that differentiation across population groups should be considered. Two populations that have often been considered are older adults and those in wheelchairs, but other population segments with distinct pedestrian needs exist. We also note that the temporal component of walking accessibility is generally neglected. Accounting for the effects of weather, nighttime, and opening hours would be a fruitful way to consider temporal aspects. Lastly, we point to several advantages of using travel time as the unit of analysis, rather than distance, for measuring pedestrian impedance, while noting that other measures such as perceived impedance may also be relevant.

In any given specific implementation of pedestrian accessibility analysis, a trade-off must be made between detailed data gathering and computational efficiency. Because of the large number of factors that influence pedestrian accessibility, gathering comprehensive data on all aspects of pedestrian accessibility may be cost-prohibitive in any given circumstance. Each analysis must consider the costs and benefits of each additional component of data to be gathered, and the overall effort should be guided by which kinds of data are most relevant to the populations and built environment contexts under study. Therefore, the most appropriate level of data gathering for each pedestrian accessibility analysis effort is a strategic consideration that should be carefully considered at the start of any pedestrian accessibility analysis project.

4.6. Appendix

Note: this is a simplified version of the review table

First Two Authors	Year	Title	Journal	Study Area	Impedance (Generalized costs)	Land-use Component		Transport Component (Used Network[6])	Individual Component	Temporal Component	Perceived or Objective
						Origins	Destinations				
Abrahams	2010	Stakeholders' Perceptions of Pedestrian Accessibility to Green Infrastructure: Fort Worth's Urban Villages	Master Thesis	Fort Worth, US	Distance, safety and physical barriers	NA	Green space	No Network	NA	NA	Perceived
Achuthan, Titheridge	2007	Measuring Pedestrian Accessibility	Proceedings of the Geographical Information Science Research UK (GISRUK) Conference	St. Albans, UK	Distance	Random	NA	Pedestrian	NA	NA	Objective
Adams	2002	Pedestrian Access	Website	NA	NA	NA	NA	No Network	NA	NA	Both
Amaya, Moulaert	2022	Assessing and Qualifying Neighborhood Walkability for Older Adults: Construction and Initial Testing of a Multivariate Spatial Accessibility Model	International Journal of Environmental Research and Public Health	Grenoble, France	Travel time, depending on age and slope	NA	Variety of POIs	Pedestrian	Age, abilities	NA	Objective
Anciaes, Nascimento	2015	Mapping Pedestrian Accessibility And The Quality Of Walking In An African City: Praia, Cape Verde	Energy, Climate and Air Quality Challenges: The Role of Urban Transport Policies in Developing Countries	Praia, Cape Verde	NA	NA	Population, jobs, variety of POIs	No Network	Income level	NA	Objective
Arranz-López, Soria-Lara	2021	An end-user evaluation to analyze the effectiveness of cartograms for mapping relative non-motorized accessibility	Environment and Planning B	Zaragoza, Spain	NA	Housing locations	Shopping	No Network	Four socio-economic groups	NA	Perceived
Arranz-López, Soria-Lara	2017	Shopping Mobility Environments: A methodological framework for integrating Shopping activity and	Journal of Transport Geography	Zaragoza, Spain	Travel time, depending on trip purpose	Housing locations	Shopping	Roadway	NA	NA	Both

[6] A distinction was made between the following three options: Roadway; Pedestrian; No network. When OpenStreetMap was used, it was considered as a Roadway network, unless the paper indicated that the data quality of pedestrian paths with their variety of features (crossings, etc.) was available and these alone were taken into account as routing network. However, this binary classification is simplified, in reality there may be many in-between degrees.

First Two Authors	Year	Title	Journal	Study Area	Impedance (Generalized costs)	Land-use Component		Transport Component (Used Network[6])	Individual Component	Temporal Component	Perceived or Objective
						Origins	Destinations				
		non-motorised accessibility in Zaragoza, Spain									
Arranz-López, Soria-Lara	2019	Measuring relative non-motorized accessibility to Shopping activities	International Journal of Sustainable Transportation	Zaragoza, Spain	Travel time, depending on population group	Housing locations	Shopping	Roadway	Four socio-economic groups	NA	Both
Arranz-López, Soria-Lara	2019	Social and spatial equity effects of non-motorised accessibility to Shopping	Cities	Zaragoza, Spain	Travel time, depending on population group	Housing locations	Shopping	Roadway	Four socio-economic groups	NA	Both
Ariza-Álvareza, Arranz-López	2019	Comparing walking accessibility variations between groceries and other Shopping activities for seniors	Research in Transportation Economics	Granada, Spain	Distance	Centroids of 100 x 100 m grid cells	Shopping	Roadway	Gender, age, abilities, car availability, household, income, household composition	NA	Both
Aultman-Hall, Roorda	1997	Using GIS for Evaluation of Neighborhood Pedestrian Accessibility	Journal of Urban Planning and Development	Hamilton, Ont., Canada	Distance	Housing locations	Schools, green space, transit stops	No Network	NA	NA	objective
Badami	2009	Urban Transport Policy as if People and the Environment Mattered: Pedestrian Accessibility the First Step	Economic and Political Weekly	India	NA	NA	NA	No Network	NA	NA	NA (rather philosophi cal paper)
Blanford, Kumar	2012	It’s a long, long walk: accessibility to hospitals, maternity and integrated health centers in Niger	International Journal of Health Geographics	Niger	Travel time	Settlemen ts	Healthcare	No Network	NA	Wet vs. dry season	Objective
Blecic, Cecchini	2013	A Design and Planning Support System for Walkability and Pedestrian Accessibility	Book “Computational Science and Its Applications” – ICCSA 2013	Lisbon, Portugal	Distance, walkability	Random	Variety of POIs	Pedestrian	NA	NA	Objective
Blecic, Cecchini	2015	Towards a Design Support System for Urban Walkability	Procedia Computer Science	Lisbon, Portugal	Distance, walkability	Random	Variety of POIs	Pedestrian	NA	NA	Objective
Blecic, Cecchini	2018	Towards Automatic Assessment of Perceived Walkability	Computational Science and Its Applications – ICCSA	Cagliari, Italy	Distance, walkability	NA	Variety of POIs	Roadway	NA	NA	Objective

First Two Authors	Year	Title	Journal	Study Area	Impedance (Generalized costs)	Land-use Component		Transport Component (Used Network[6])	Individual Component	Temporal Component	Perceived or Objective
						Origins	Destinations				
Boakye-Dankwa, Barnett	2019	Associations Between Latent Classes of Perceived Neighborhood Destination Accessibility and Walking Behaviors in Older Adults of a Low-Density and a High-Density City	Journal of Aging and Physical Activity	Brisbane + Hong Kong	Travel time	Housing locations	Variety of POIs	No Network	Agee, gender, education, socio-economic status	NA	Perceived
Borowska-Stefańska, Wiśniewski	2017	Pedestrian Accessibility to Parks in Łódź	Studia Miejskie	Łódź, Poland	Travel time	Housing locations	Green space	Roadway	Age	NA	Objective
Carpio-Pinedo, Benito-Moreno	2021	Beyond land use mix, walkable trips. An approach based on parcel-level land use data and network analysis	Journal of Maps	Madrid Metropolitan Area, Spain	Distance	Trip generating land use categories	Shopping	Roadway	NA	NA	Objective
Chandra, Jimenez	2017	Accessibility evaluations for nighttime walking and bicycling for low-income shift workers	Journal of Transport Geography	El Paso, Texas	Travel time	Transit stops	Jobs	Pedestrian	Income	Night-time	Objective
Cheng, Caset	2019	Investigating walking accessibility to recreational amenities for elderly people in Nanjing, China	Transportation Research Part D: Transport and Environment	Nanjing, China	Distance	Housing locations	Leisure	No Network	Socio-economic variables	NA	Objective
Colclough	2009	Modelling Pedestrian Accessibility using GIS Techniques to Assess Development Sustainability	AECOM	West Northamptonshire, England	Travel time	Housing locations	Variety of POIs	Pedestrian	Age	NA	Objective
D'Orso, Migliore	2018	A GIS-Based Method to Assess the Pedestrian Accessibility to the Railway Stations	Book "Computational Science and Its Applications" – ICCSA 2018	Palermo, Italy	Distance, walkability	Transit stops	NA (POIs are only visualized)	Pedestrian	NA	NA	Objective
Damurski, Pluta	2020	Pedestrian accessibility of services as a measure of territorial cohesion at the neighbourhood level	Bulletin of Geography. Socio-economic Series	Poland	Travel time	Housing locations	Variety of POIs	Pedestrian	Housing types, city sizes	NA	Both
Eizaguirre-Iribar, Igiñiz	2016	A multilevel approach of non-motorised accessibility in disused railway systems: The case-study of the Vasco-Navarro railway	Journal of Transport Geography	Basque Country, Spain	Travel time	Housing locations	Variety of POIs	Roadway	NA	NA	Objective

First Two Authors	Year	Title	Journal	Study Area	Impedance (Generalized costs)	Land-use Component		Transport Component (Used Network[6])	Individual Component	Temporal Component	Perceived or Objective
						Origins	Destinations				
Erath, van Eggermond	2015	Modelling for Walkability. Understanding pedestrians' preferences in Singapore.	Presentation. International Conference on travel behavior research	Singapore	Travel time	Random	NA	Pedestrian	Age, gender, ethnicity	NA	Perceived
Erath, van Eggermond	2017	Introducing the Pedestrian Accessibility Tool: Walkability Analysis for a Geographic Information System	Transportation Research Record: Journal of the Transportation Research Board	Singapore	Travel time	Buildings	Variety of POIs	Pedestrian	NA	Weather conditions	Both
Foda, Osman	2010	Using GIS for Measuring Transit Stop Accessibility Considering Actual Pedestrian Road Network	Journal of Public Transportation	Alexandria, Egypt	Distance	NA	Transit stops	Roadway	NA	NA	Objective
Foti, Waddell	2012	A Generalized Computational Framework for Accessibility: From the Pedestrian to the Metropolitan Scale	Proceedings of the 4th TRB Conference on Innovations in Travel Modeling	9-County Bay Area, California	Distance	NA	Variety of POIs	Roadway	NA	NA	Objective
Gaglione, Cottrill	2021	Urban services, pedestrian networks and behaviors to measure elderly accessibility	Transportation Research Part D: Transport and Environment	Naples, Italy & Aberdeen, Scotland	Perceived time, depending on walkability	NA	Variety of POIs	Pedestrian	Age	NA	Objective
Gaglione, Gargiulo	2019	Elders' quality of life and urban accessibility. A method proposal for spatial planning.	Journal of Land Use, Mobility and Environment	Naples, Italy	Distance	NA	Variety of POIs	Pedestrian	Age	NA	Objective
García-Palomares, Gutiérrez	2013	Walking Accessibility to Public Transport: An Analysis Based on Microdata and GIS	Environment and Planning B: Planning and Design	Madrid, Spain	Distance	Housing locations	Transit stops	Roadway	Gender, age, car ownership, nationality	NA	Both
Goldsberry, Duvall	2010	Visualizing nutritional terrain: a geospatial analysis of pedestrian produce accessibility in Lansing, Michigan, USA	Geocarto International	Lansing, Michigan, USA	Distance	Housing locations	Shopping	Roadway	NA	NA	Objective
Goodwin	2005	Where the Sidewalk Begins: Pedestrian Accessibility Analysis in Suburban Cincinatti	Master Thesis	Cincinatti, Ohio, USA	Distance and availability of sidewalks	Housing locations	Shopping	Roadway	Housing types	NA	Objective
Grecu, Morar	2013	A Decision Support System for Improving Pedestrian Accessibility in Neighborhoods	Procedia - Social and Behavioral Sciences	Romania	NA	Housing locations	Variety of POIs	No Network	NA	NA	Objective

First Two Authors	Year	Title	Journal	Study Area	Impedance (Generalized costs)	Land-use Component		Transport Component (Used Network[6])	Individual Component	Temporal Component	Perceived or Objective
						Origins	Destinations				
Higgins, Nel	2019	Slope, Layers, And Walkability: Estimating The Link Between Pedestrian Accessibility And Land Values In The Morphology Of High Density Cities	Urban Morphological Methods and Techniques	HongKong Island	Distance	Buildings	Buildings, Variety of POIs	Roadway	Household income	Spatio-Temporal Hedonic Regression Model	Objective
Holzer	2018	Analyzing Pedestrian Accessibility Using QGIS and OpenStreetMaps Data	Website	St. Paul, Minnesota	Distance	Buildings	Restaurants	Pedestrian	Age	NA	Objective
Iacano, Krizek	2008	Access to Destinations: How Close is Close Enough? Estimating Accurate Distance Decay Functions for Multiple Modes and Different Purposes	Report	South Minneapolis, US	Different decay functions (time and distance)	Housing locations	Restaurants	No Network	NA	NA	Perceived
Iacano, Krizek	2010	Measuring non-motorized accessibility: issues, alternatives, and execution	Journal of Transport Geography	South Minneapolis, US	Comparison of time and distance	Building blocks	Jobs, shopping, entertainment, restaurants	Pedestrian	Trip purpose	NA	Both
Jang, Kim	2020	Urban Green Accessibility Index: A Measure of Pedestrian-Centered Accessibility to Every Green Point in an Urban Area	International Journal of Geo-Information	New York & San Francisco, US	Distance, walkability	NA	Green space	Roadway	NA	NA	Objective
Jehle, Pajares	2020	Incorporating the four accessibility components into an interactive accessibility instrument	Master Thesis	Munich, Germany	Travel time	Housing locations	Variety of POIs	Pedestrian	Age, abilities	Day vs. night	Objective
Jonietz, Timpf	2012	Incorporating the Influence of Walkability into a Model of Pedestrian Accessibility	Bookchapter in "Transportation Demand Management"	Augsburg, Germany	Distance, walkability	Big city-center carparks	Shopping	Pedestrian	NA	NA	Objective
Kang	2015	The effects of spatial accessibility and centrality to land use on walking in Seoul, Korea	Cities	Seoul, Korea	Distance	Survey spots of pedestrian volumes	Buildings (differentiated by landuse)	Roadway	NA	Weekdays vs. Saturday	Both
Kuzmyak, Baber	2006	Use of Walk Opportunities Index to Quantify Local Accessibility	Transportation Research Record: Journal of the Transportation Research Board	Baltimore Metropolitan Area, US	Distance, slope, crossings	Housing locations	Jobs, variety of POIs	Roadway	demographic characteristics	NA	Objective

First Two Authors	Year	Title	Journal	Study Area	Impedance (Generalized costs)	Land-use Component		Transport Component (Used Network[6])	Individual Component	Temporal Component	Perceived or Objective
						Origins	Destinations				
Laakso, Sarjakoski	2011	Improving Accessibility Information in Pedestrian Maps and Databases	Cartographica: The International Journal for Geographic Information and Geovisualization	Finnland	NA	NA	NA	Pedestrian	Abilities	NA	NA
Laasko, Sarjakoski	2013	An Information Model for Pedestrian Routing and Navigation Databases Supporting Universal Accessibility	Cartographica: The International Journal for Geographic Information and Geovisualization	International	NA	NA	NA	Pedestrian	Abilities	Presence of street lights	NA
Li, Cebe	2018	A Semi-Automated Method to Generate GIS-Based Sidewalk Networks for Asset Management and Pedestrian Accessibility Assessment	Transportation Research Record	Atlanta, Georgia	Travel time, pedestrian infrastructure	One example OD pair	One example OD pair	Pedestrian	NA	NA	Objective
Liang, Chen	2017	Walking accessibility of urban parks in a compact megacity	Institution of Civil Engineers	Shanghai, China	Distance	Housing locations, roadway junctions	Green space	Roadway	NA	NA	Objective
Liu, Higgs	2021	A Generalized Framework for Measuring Pedestrian Accessibility around the World Using Open Data	Geographical Analysis	25 cities across the globe	Distance	Population hexagons	Shopping, transit stops, green space	Roadway	NA	NA	Objective
Marquet, Bedoya	2017	Local accessibility inequalities and willingness to walk in Latin-American cities: Findings from Medellín, Colombia	International Journal of Sustainable Transportation	Medellin, Columbia	Travel time	NA	Trip purposes: occupational, personal, return home	No Network	Gender, age, education level, employment status, and economic strata	Time of Day	Objective
Morar, Radoslav	2014	Assessing Pedestrian Accessibility To Green Space Using GIS	Transylvanian Review of Administrative Sciences	Timișoara, Romania	Distance, threshold depends on size of park	Housing locations	Green space	Roadway	housing type / social groups	NA	Objective
Orellana, Bustos	2020	Walk'n'roll: Mapping street-level accessibility for different mobility	Journal of Transport & Health	Cuenca, Ecuador	inclusive design	NA	NA	No Network	Abilities	NA	Objective

First Two Authors	Year	Title	Journal	Study Area	Impedance (Generalized costs)	Land-use Component		Transport Component (Used Network[6])	Individual Component	Temporal Component	Perceived or Objective
						Origins	Destinations				
		conditions in Cuenca, Ecuador									
Páez, Anjum	2020	Comparing distance, time, and metabolic energy cost functions for walking accessibility in infrastructure-poor regions	Journal of Transport Geography	Kenya	Travel time, metabolic energy	Housing locations	Water sources	Pedestrian	NA	NA	Objective
Pajares, Büttner	2021	Accessibility by proximity: Addressing the lack of interactive accessibility instruments for active mobility	Journal of Transport Geography	International	Travel time	Flexible, but mostly residences	Variety of POIs, population	Roadway	Age, abilities	NA	Objective
Papa, Carpentieri	2018	Measuring walking accessibility to public transport of the elderly: the case of Naples	Journal of Land Use, Mobility and Environment	Naples, Italy	Travel time	Housing locations	Transit stops	Roadway	Age	NA	Objective
Pearce, Matsunaka	2021	Comparing accessibility and connectivity metrics derived from dedicated pedestrian networks and street networks in the context of Asian cities	Asian Transport Studies	International	Pedshed, pedestrian route directness, or directional reach	NA	Transit stops	Pedestrian	NA	NA	Objective
Pearce, Matsunaka	2021	Utilising Dedicated Pedestrian Networks To Understand The Relationship Between Accessibility And Pedestrian Density In Asian Cities	International Journal of Transport Development and Integration	International	Pedshed, pedestrian route directness, or directional reach	NA	Transit stops	Pedestrian	NA	NA	Objective
Reyes, Páez	2014	Walking accessibility to urban parks by children: A case study of Montreal	Landscape and Urban Planning	Montreal, Canada	Straight line distance	Housing locations	Green space	No Network	Age, gender, income class, family structure,	NA	Perceived
Roblot, Boisjoly	2021	Participation in Shared Mobility: An Analysis of the Influence of Walking and Public Transport Accessibility to Vehicles on Carsharing Membership in Montreal, Canada	Transportation Research Record	Montreal, Canada	Travel time	Canadian Census DAs	Carsharing stations	Roadway	NA	NA	Objective

First Two Authors	Year	Title	Journal	Study Area	Impedance (Generalized costs)	Land-use Component		Transport Component (Used Network[6])	Individual Component	Temporal Component	Perceived or Objective
						Origins	Destinations				
Rossetti, Tiboni	2020	Measuring Pedestrian Accessibility to Public Transport in Urban Areas: A GIS-based Discretisation Approach	European Transport	Brescia, Italy	Travel time	NA	Transit stops	Pedestrian	NA	NA	Objective
Rossetti, Tiboni	2015	Pedestrian mobility and accessibility planning: some remarks towards the implementation of travel time maps	City Safety Energy Journal	Brescia, Italy	Travel time	NA	Transit stops	Pedestrian	NA	NA	Objective
Saghapour, Moridpour	2017	Measuring Walking Accessibility in Metropolitan Areas	Transportation Research Record	Melbourne, Australia	Distance	Statistical areas	Variety of POIs	Roadway	NA	NA	Objective
Saghapour, Moridpour	2018	Enhancing active transport demand Modelling by incorporating accessibility measures	Cities	Melbourne, Australia	Distance	Statistical areas	Variety of POIs	Roadway	NA	NA	Objective
Saghapour, Moridpour	2019	Sustainable transport in neighbourhoods: effect of accessibility on walking and bicycling	Transportmetrica A: Transport Science	Melbourne, Australia	Distance	Statistical areas	Variety of POIs	Roadway	NA	NA	Objective
Seisen-berger	2021	Evaluating walking accessibility and equity to essential services with and without competition using the interactive accessibility instrument GOAT	Master Thesis	Munich, Germany	Travel time	Housing locations	Variety of POIs	Pedestrian	Socio-economic variables	NA	Objective
Sevtsuk, Kalvo	2016	Pedestrian accessibility in grid layouts: the role of block, plot and street dimensions	Urban Morphology	NA	Distance	Plots	Plots	Roadway	NA	NA	Objective
Sinagra	2019	Development of pathNav: A Pedestrian Navigation Tool that Utilizes Smart Data for Improved Accessibility and Walkability	Transit IDEA	Pittsburgh, Pennsylvania	Distance, walkability	NA	NA	Pedestrian	Individual calibration	NA	Objective
Stewart	2016	Using Pedestrian Accessibility Indicators to Locate Schools: A Site Suitability Analysis in Greenville County, South Carolina	Master Thesis	Greenville, South Carolina	Distance	Housing locations	Schools	Roadway	NA	NA	Objective

First Two Authors	Year	Title	Journal	Study Area	Impedance (Generalized costs)	Land-use Component		Transport Component (Used Network[6])	Individual Component	Temporal Component	Perceived or Objective
						Origins	Destinations				
Sun, Haining	2015	Comparing the perception with the reality of walking in a hilly environment: an accessibility method applied to a University campus in Hong Kong	Geospatial Health	Hong Kong	Travel time (perceived and actual)	Buildings	Green space	Pedestrian	NA	NA	Both
Tal, Handy	2012	Measuring Nonmotorized Accessibility and Connectivity in a Robust Pedestrian Network	Transportation Research Record	Davis, California	Distance	Housing locations	Schools, shopping	Pedestrian	NA	NA	Objective
Tang, Wong	2020	Walking accessibility to neighborhood open space in a multi-level urban environment of Hong Kong	Environment and Planning B	Hong Kong	Travel time / distance	Housing locations	Green space	Pedestrian	NA	NA	Objective
Tasic, Musunuru	2014	Quantifying Accessibility of Nonmotorized Transportation Modes in Recreational Areas: Case Study of Mill Creek Canyon, Utah	Journal of Park and Recreation Administration	Mill Creek Canyon, Utah	Travel time	Parking lots	Leisure	Pedestrian	NA	NA	Objective
Tiran, Lakner	2019	Modelling walking accessibility: A case study of Ljubljana, Slovenia	Moravian Geographical Reports	Ljubljana, Slovenia	Travel time	Housing locations	Variety of POIs	Roadway	NA	NA	Objective
Vale, Pereira	2017	The influence of the impedance function on gravity-based pedestrian accessibility measures: A comparative analysis	Environment and Planning B	Santarem, Portugal	Distance	Buildings	Schools	Roadway	NA	NA	Objective
Vale, Saraiva	2015	Active accessibility: A review of operational measures of walking and cycling accessibility	Journal of Transport and Land Use	International	NA	NA	NA	No Network	NA	NA	Restricted to objective measures
van Eggermond, Erath	2016	Pedestrian and transit accessibility on a micro level: Results and challenges	Journal of Transport and Land Use	Singapore	Travel time	Housing locations	Jobs, buildings	Pedestrian	NA	NA	Objective
Verma, Verma	2019	Measuring accessibility of various facilities by walking in world's largest mass religious gathering - Kumbh Mela	Sustainable Cities and Society	Ujjain, India	Travel time and distance	591 square blocks	Restaurants, shopping, religion	No Network	NA	NA	Objective
van der Vlugt, Curl	2022	The influence of travel attitudes on perceived walking accessibility and walking behavior	Travel Behaviour and Society	Hamburg, Germany	WalkScore measurement	100x100 meter grid	Variety of POIs	No Network	Income, education, age, gender	Weather	Perceived

First Two Authors	Year	Title	Journal	Study Area	Impedance (Generalized costs)	Land-use Component		Transport Component (Used Network[6])	Individual Component	Temporal Component	Perceived or Objective
						Origins	Destinations				
Wilhelm	2007	Analysis of pedestrian accessibility as applied to Spokane city parks	Thesis	Spokane, Washington	Travel time, walkability	NA	Green space	Pedestrian	Abilities	NA	Objective
Xu	2014	A Gis-Based Pedestrian Network Model For Assessment Of Spatial Accessibility Equity And Improvement Prioritization And Its Application To The Spokane Public Transit Benefit Area	Thesis	Spokane, Washington	Distance	Census block centroids	Variety of POIs	Pedestrian	Car ownership	NA	Objective
Yang, Tan	2021	Evaluating Accessibility Benefits of Opening Gated Communities for Pedestrians and Cyclists in China: A Case Study of Shanghai	Sustainability	Shanghai, China	Distance	Housing locations	Variety of POIs	Roadway	NA	NA	Objective
Yang, Wang	2018	Walking accessibility and property prices	Transportation Research Part D: Transport and Environment	Xiamen, China	Travel time	Housing locations	Variety of POIs	Roadway	NA	NA	Objective
Zahra, Ahyudanari	2021	Measuring pedestrian accessibility of Transit Oriented Development area in surabaya (a study case: Joyoboyo Terminal)	IOP Conf. Series: Earth and Environmental Science	Surabaya, Indonesia	Distance	NA	Transit stops	Roadway	NA	NA	Objective
Zecca, Gaglione	2020	Pedestrian routes and accessibility to urban services: An urban rhythmic analysis on people’s behaviour during the Covid-19	Journal of Land Use, Mobility and Environment	Aberdeen, Scotland	Unclear	Housing locations	Shopping	Pedestrian	NA	NA	Objective
Zuo, Wei	2018	Determining transit service coverage by non-motorized accessibility to transit: Case study of applying GPS data in Cincinnati metropolitan area	Journal of Transport Geography	Cincinatti, Ohio, USA.	Distance	NA	Transit stops	Roadway	NA	NA	Objective

5. Connecting people and places: Analysis of perceived pedestrian accessibility to railway stations by Bavarian case studies

Ulrike Jehle, Cara Coetzee, Benjamin Büttner, Elias Pajares, Gebhard Wulfhorst (2022): Connecting people and places: Analysis of perceived pedestrian accessibility to railway stations by Bavarian case studies. Journal of Urban Mobility, 2, 100025. https://doi.org/10.1016/j.urbmob.2022.100025.

Abstract

Walking connects different modes of transport and acts as the main feeder for public transport. Nonetheless, ensuring high-quality accessibility for pedestrians to railway stations is seldom evaluated beyond measurable factors such as walking distance and time. Although several studies found differences in calculated and perceived accessibility, little research has so far focused on the factors that are influencing perceived pedestrian accessibility and thus causing these differences. In order to contribute to the current efforts of conceptualising perceived accessibility, this study explores the factors which determine whether or not people walk to train stations. Potential influencing factors were first derived from a literature review and clustered into six quality criteria (directness, simplicity, traffic safety, security, comfort and built environment). Then, on-site and online surveys were conducted in five Bavarian towns (Germany) to understand the importance of the identified factors and how this differs between different people and places. The results confirm that above all comfort, safety and security factors play an important role for pedestrian accessibility. In addition, significant differences were found between different age groups and city sizes.

5.1. Introduction

All trips begin on foot. Walking is especially important for public transport trips: walking overall serves as the main feeder for public transport and thus also for the railway system. Although the proportion of pedestrians can vary considerably, in Europe typically, more than 50% of trips to and from railway stations are made on foot (Ceder 1998; La Paix and Geurs 2014). Travellers that reach the railway station by car, bicycle or bus, still have to walk the last metres to the platform. In general, public transport is only attractive if the whole trip chain is competitive with other modes of transport, especially cars (Keijer and Rietveld 2000). Thus adequate pedestrian infrastructure to and at public transport stops is crucial to foster public transport usage. Evidently, walking is a key element of railway stations and mobility hubs: it allows different transport modes and nodes to be connected, thereby enabling intermodality and promoting sustainable mobility. Apart from the feeder role it has to public transport, active mobility brings many health benefits for its users (Lin, Sun, and Li 2015). Moreover, walking is for free, uses urban space efficiently, is environmentally friendly, allows for easy interaction with other people, strengthens the local economy and requires comparatively little investment (FGSV 2014; Jou 2011).

Pedestrian accessibility can be defined as the ease with which certain destinations can be reached by walking (Koenig 1980; Niemeier 1997). To firstly analyse and secondly enable the ease of reaching the stations in reality, a shift from mobility-based planning to accessibility-based planning is advisable. This shift can already be observed in quite some fields and studies (Handy 2020; Merlin, Levine, and Grengs 2018). The quality of pedestrian accessibility is dependent on the location of the destination, the network connectivity (Geurs and van Wee 2004; Kathuria et al. 2019), and the resulting trip duration. However, pedestrian accessibility is not only influenced by time-related factors. A study by Kathuria et al. (2019) shows that the public transport ridership increases with improved walkway quality. The surrounding environment of the walkway also impact the perceived pedestrian accessibility (Bivina, Gupta, and Parida 2020; Erath et al. 2021; Gupta, Bivina, and Parida 2022; Pueboobpaphan, Pueboobpaphan, and Sukhotra 2022). For example, if a route leads through an unpleasant area, it might feel longer than it actually is (Bahn.Ville 2-Konsortium 2010; Ralph et al. 2020). Lastly, the health and well-being of the pedestrian determine whether some routes are accessible or not (Brons, Givoni, and Rietveld 2009; De Vos et al. 2013). If a person is mobility-impaired or has other limitations, some paths may be not accessible at all. Overall, it can be said that good pedestrian accessibility is essential to making walking to railway stations an attractive option. This highlights the usefulness of comprehensive accessibility studies in this regard.

While some factors influencing walking, such as distance, footpath width and presence of street lights can easily be measured, others such as the attractiveness of the surrounding environment are harder to evaluate. In fact, even if evaluation criteria for those factors influencing walking are found and measured, it does not necessarily mean that they are perceived the same by (all) pedestrians. These differences in calculated and perceived accessibility were posed in several studies and are attracting the interest of a rising number of researchers (such as Curl, Nelson, and Anable 2015; Damurski, Pluta, and Zipser 2020; Lättman, Olsson, and Friman 2018; Pot, van Wee, and Tillema 2021; Jean Ryan and Pereira 2021; Mark Ryan et al. 2016). In contrast to calculated accessibility (using spatial data to compute accessibility indicators), perceived accessibility describes how people actually experience the potential to participate in spatially dispersed opportunities (Pot, van Wee, and Tillema 2021) and is attempted to be derived through surveys and mobility behaviour studies. While calculated pedestrian accessibility to transport stations has been discussed at length in literature and is applied in practice, little research has focused on perceived factors influencing pedestrian accessibility (Curl, Nelson, and Anable 2015; J. Ryan and Pereira 2021).

The purpose of this study is to answer the following research questions: Which factors influence the perceived pedestrian accessibility of railway stations? How does this differentiate for different people and places? Although this exploratory study focuses on perceived pedestrian accessibility to railway stations in Bavaria, the results may also be transferable to pedestrian accessibility to other destinations in other regional contexts. Therewith, this paper aims to contribute to current efforts (e.g. by Pot, van Wee, and Tillema 2021; Jean Ryan and Pereira 2021) of conceptualising perceived accessibility and further advancing the shift from mobility-based to accessibility-based planning (Pot, van Wee, and Tillema 2021).

This paper is structured as follows: *Section 5.2* will start with a literature review, followed by the explanation of the design of this study in *Section 5.3*. *Section 5.4* summarises the results, which are later discussed in *Section 5.5* with regard to their relevance for the research question. Finally, *Section 5.6* concludes the paper and points out future needs for action – for research and practice.

5.2. Literature review

The following literature review explores how railway stations interact with the city (*Section 5.2.1*), how pedestrian accessibility (to railway stations) can be evaluated (*Section 5.2.2*), how measured and perceived pedestrian accessibility differ (*Section 5.2.3*), and how this is related to the concept of walkability (*Section 5.2.4*). The identified research gaps are summarized in *Section 5.2.5*.

5.2.1. Functions of railway stations

In contrast to travelling by car, bicycle or foot, public transport does not allow for spontaneous interactions with the external environment, as the routes and entry and exit points are fixed. Thus, railway stations are the portals into places and their opportunities for many people (Bertolini 2008). In the sense of transit oriented development (Vale 2015), a railway station has to be well-connected, not only to other nodes on the transport network, but also to its surroundings (Crockett and Hounsell 2005) - especially for pedestrians (Brons, Givoni, and Rietveld 2009), because at the latest upon entering the station, everyone becomes a pedestrian. In other words, only if network connectivity is met with station accessibility does the public transport system as a whole flourish.

However, reducing a railway station to its mobility function denies its potential as a location in its own right: they are and have to be more than nodes on a transport network (Bertolini 1996). If designed well, the railway stations are places of service, leisure, commerce and communication (Zemp et al. 2011). While the high accessibility levels ideally given at a railway station attract offices and housing, the high volumes of passengers travelling through railway stations generate demand for retail and gastronomy. Vitalising the surroundings of railway stations in this way also augments the objective and perceived sense of security (Beckmann, Witte, and Wulfhorst 1999). Therefore such an intense and diverse functional use not only enhances the overall attractiveness of the location, but also contributes to the local economy around the railway station (Zemp et al. 2011). The many commercial opportunities together with the higher sense of security in turn increase the attractiveness of public transport and spawn higher demand for this mode (Tiwari 2015). All this makes a railway station a lively place in a city that contributes to a city's character and is more than only a stop on a transit line (Bahn.Ville 2-Konsortium 2010; Wulfhorst 2003).

The importance of walking in enhancing the attractiveness of a railway station is clear: "the larger the number of people that can reach a certain station in a short amount of time, the higher the density of functions around it" (Wenner et al. 2020). The same applies the other way around. Good pedestrian accessibility of the station surroundings thereby increases the catchment area and thus the potential number of public transport passengers (Hillnhütter 2016).

5.2.2. Concept of pedestrian accessibility

Accessibility was first defined as the "potential of opportunities for interaction" by Hansen (1959) and later specified by Geurs and van Wee (2004) as the "extent to which land use and transport systems enable (groups of) individuals to reach activities or destinations by means of a (combination of) transport mode(s)". Accessibility is characterised by land-use, transportation, temporal and individual components (Geurs and van Wee 2004). Although there are some overlaps, the first two describe the *place*, while the last two mainly capture how *people* with individual preferences and differing temporal constraints can access destinations. In the context of time-geography (Hägerstrand 1970), the terms *place-based accessibility* (Hu and Downs 2019) and *person-based accessibility* (Fransen and Farber 2019; Järv et al. 2018; Páez, Scott, and Morency 2012) are used to specify these to parts. Individual and temporal factors such as income, age, gender, educational level, car and time availability, as well as the time of the day and year, all influence how people perceive their access to certain destinations (e.g. railway stations) by different modes - and consequently their mobility decisions. According to Handy and Niemeier (1997), “the key is to measure accessibility in terms that matter to people in their assessment of the options available to them”. For the transportation component, this means knowing what features of different modes of transport are important to people (Handy and Clifton 2000).

Pedestrian accessibility outlines the concept for walking specifically, as the accessibility of this mode is determined differently. Pedestrian accessibility is not only influenced by objective, measurable characteristics, but also subjective, perceived characteristics, such as sense of safety or comfort (Lin, Sun, and Li 2015). Comfort in this sense is defined as the person’s level of ease, convenience and contentment while walking (Alfonzo 2005). Walking attractiveness includes, but is not limited to, unobstructed and safe accessibility with good connectivity, safe crossing opportunities and well-designed footpaths that are easy to walk on (Lo 2009; Ujang and Zakariya 2015). There is rising certainty that pedestrian accessibility is strongly connected to perceived quality levels of the land use and transport systems (Arslan et al. 2018; Gkavra et al. 2019; Liang and Cao 2019) and dependent on individual characteristics, capabilities, attitudes and preferences (Pot, van Wee, and Tillema 2021). Whether or not an individual chooses to walk to a destination is therefore influenced by various factors, ranging from large elements such as the type of urban form to small elements such as street furniture (Alfonzo 2005; Arslan et al. 2018) and external conditions such as weather. Due to their slow speed and direct interaction with the environment, pedestrians are generally more aware and sensitive to their surroundings than drivers, which is highly related to the individual walking comfort (Handy et al. 2002). Therefore, a stronger focus on micro-features is needed to fully understand the interactions (Bivina, Gupta, and Parida 2020; Clifton, Livi, and Rodriguez 2007).

Pedestrian accessibility in relation to public transport stations has been investigated in recent studies, e.g. by Bivina, Gupta, and Parida (2019), Kathuria et al. (2019), Sarker, Mailer, and Sikder (2019), Bivina, Gupta, and Manoranjan (2020), Rossetti et al. (2020), Gupta, Bivina, and Parida (2022) and Pueboobpaphan, Pueboobpaphan, and Sukhotra (2022), generating similar results as the general pedestrian accessibility studies. Sarker, Mailer, and Sikder (2019) found that especially the working population usually chooses the most direct and shortest route. In addition to route directness, micro-scale (e.g. sidewalk availability, surface quality) and meso-scale built environment factors (e.g. population density and land use diversity) were found to have an positive impact on access mode choice (Gupta, Bivina, and Parida 2022; Kathuria et al. 2019), while the effects of micro-scale factors were more significant (Bivina, Gupta, and Parida 2020). Especially safety and security factors were found as the most influential regarding pedestrian accessibility (Bivina, Gupta, and Parida 2019; Gupta, Bivina, and Parida 2022). Improving the walking environment can therewith increase the distance people are willing to walk, thus also increasing the service coverage area of stations (Pueboobpaphan, Pueboobpaphan, and Sukhotra 2022) and consequently the ridership numbers (Kathuria et al. 2019).

Rossetti et al. (2020) proposed a method to calculate pedestrian accessibility to railway stations by creating detailed pedestrian isochrones and calculate how many inhabitants have access to the public transport system within a certain time, while Pueboobpaphan, Pueboobpaphan, and Sukhotra (2022) found that acceptable walking distances was less for Bangkok than suggested by standard methods. This again hints at the fact that calculated and perceived accessibility may differ.

5.2.3. Mismatch between calculated and perceived accessibility

Calculated accessibility refers to the calculation of accessibility by the use of accessibility indicators based on spatial data. This term is e.g. used by Jean Ryan and Pereira (2021) and Pot, van Wee, and Tillema (2021), while others use terms like *objective accessibility* (Lättman, Olsson, and Friman 2018) or *measured accessibility* (M. Ryan et al. 2016). Anyhow, as all models and indicators are somehow generated by humans, they can never be fully *objective* (Haugen et al. 2012; J. Ryan and Pereira 2021; Schwanen and de Jong 2008). Also, the term *measured* can be misleading, as accessibility itself cannot be measured by a simple device, as e.g. sidewalk width. Instead, technical indicators are needed that somehow *calculate* accessibility by the use of data and certain input parameters. Therefore, the authors decided to go with the term *calculated accessibility*, as it is also recommended by Jean Ryan and Pereira (2021) and Pot, van Wee, and Tillema (2021).

When referring to how individuals perceive their ease of reaching destinations, the terms *subjective accessibility* (Damurski, Pluta, and Zipser 2020), *perceived accessibility* (Lättman, Olsson, and Friman 2018; Pot, van Wee, and Tillema 2021; M. Ryan et al. 2016; van der Vlugt, Curl, and Wittowsky 2019), *self-reported accessibility* (Curl, Nelson, and Anable 2015; J. Ryan and Pereira 2021) or *experienced accessibility* (Chorus and de Jong 2011) are used. While *subjective accessibility* mainly serves as a counterpart to *objective accessibility*, *self-reported accessibility* refers to survey results, which is the method used in most studies to derive perceived accessibility, but the term focuses on the method rather than the outcome. Regarding *experienced* and *perceived accessibility*, the authors consider both terms as fitting but decided for *perceived accessibility*, as the majority of existing literature also used this term.

Pot, van Wee, and Tillema (2021) define perceived accessibility as “the perceived potential to participate in spatially dispersed opportunities”. This definition is also used in course of this paper, with specification to railway stations.

Regardless of the terminology, several studies found a mismatch between different accessibility metrics (Curl, Nelson, and Anable 2015; Damurski, Pluta, and Zipser 2020; Gebel et al. 2011; Lättman, Olsson, and Friman 2018; McCormack et al. 2008; Pot, van Wee, and Tillema 2021; J. Ryan and Pereira 2021; M. Ryan et al. 2016). While attractiveness of public transport is classified by means of travel time, quality of service, waiting times and comfort, only a few measurable factors such as travel distance and/or travel time are usually considered for walking. Although there are reasons to believe that these factors are not necessarily the most appropriate when it comes to accessibility by active modes (Páez et al. 2020): “Crucial to determining the acceptable distance in a given situation is not only the actual physical distance, but also to a great extent the experienced distance” (Gehl 1987). In contrast to *place-based accessibility*, *calculated accessibility* is not excluding the individual and temporal component per definition. But as the perceived factors are not even close to being fully researched, there are only few studies (D’Orso and Migliore 2018; Erath et al. 2017; Gaglione, Cottrill, and Gargiulo 2021) considering walkability factors. Thus, there is a tendency to overestimate accessibility levels (Curl, Nelson, and Anable 2015; J. Ryan and Pereira 2021).

5.2.4. Walkability

Besides *pedestrian accessibility*, the term *walkability* is often used in literature to make a statement about how walking-friendly an area is. The Walk Score ® index, which is very often used to assess walkability, also uses gravity-based accessibility measures (Hall and Ram 2018). While the Walk Score ® itself can be considered as an ‘objective’ measure, especially when it comes to perceptions, more research can be found in the walkability field than in perceived pedestrian accessibility.

The American Planning Association (2006) defines walkability as: “A place in which residents of all ages and abilities feel that it is safe, comfortable, convenient, efficient, and welcoming to walk, not only for recreation but also for utility and transportation”. The definition and the term, which already contains the word *ability*, hints at the fact that age and personal abilities have an impact on the walkability. Although those factors are also included in the individual component of accessibility, the term *walkability* puts additional emphasis on the perception of the people walking (as stated in the definition: how people “feel”). In this context, researchers (e.g. Blečić et al. 2015; Fancello, Congiu, and Tsoukiàs 2020; Reyer et al. 2014) also refer to the capability-approach by Nussbaum (2003). According to Sen (1980), *capabilities* cover "what people are actually able to do and to be". The individual capabilities of a person are based on internal and external factors: (1) the ability, person's internal power, detained but not necessarily exercised, to do and to be, and (2) the opportunity, presence of external conditions which make the exercise of that power possible (Blečić et al. 2015). In order that a person is capable of doing something, e.g. walking to the railway station, both the internal and external factors need to be in line. The concept of capability is tightly intertwined with the individual component of accessibility (Vecchio and Martens 2021), in turn influencing perceived accessibility (J. Ryan, Wretstrand, and Schmidt 2019).

Even though there is no standard definition for walkability (Forsyth 2015) and not all of them include the availability of destinations, plenty the results are also useful for understanding pedestrians perceptions that may also influence perceived pedestrian accessibility.

As for this research the availability of specific destinations, namely railway stations, was of fundamental importance, the term *pedestrian accessibility* is used to describe the walking conditions to those. To emphasise the individual perceptions of the pedestrians, the word *perceived* is added.

5.2.5. Research gap(s)

Good pedestrian accessibility is paramount in order to encourage people walk to the railway station and increase the users of the railway offer. There is a common agreement, that perceived factors are crucial in this regard and the solely consideration of calculated measures leads to distorted results. However, in order to include the perceived factors in the analysis of accessibility, they must first be explored and fully understood - this is the stage of work that researchers in the field are currently in. To current point in time, it is neither clear which factors are the most important ones when it comes to perceived accessibility nor how this differs for different people and at different places.

5.3. Research framework and methodology

This research project aims to contribute to this/these research gap(s) and to explore factors influencing perceived pedestrian accessibility to one specific destination: railway stations. Five municipalities are therefore chosen as study areas (*Section 5.3.1*). First, a general set of quality criteria (*Section 5.3.2*) is derived and developed from literature and subsequently used as a hypothesis framework to evaluate the perceived accessibility. Then, surveys on the perceived pedestrian accessibility are conducted in the selected study areas (*Section 5.3.3*). The results are analysed in order to better understand how individual people at different places perceive accessibility (*Section 5.3.4*). The following sections and *Figure 17* give more detail on each part of the methodology.

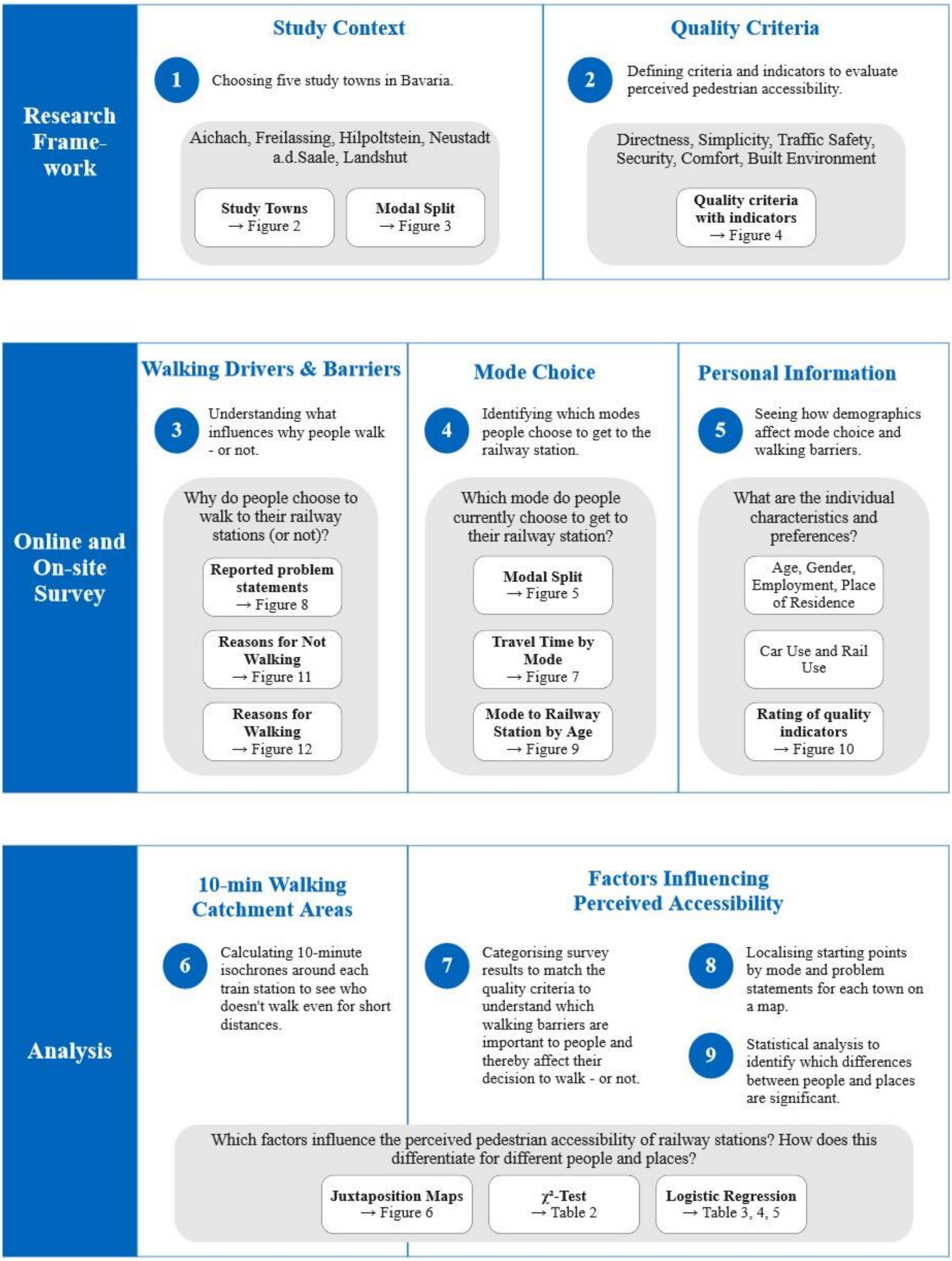


Figure 17: Methodological steps

5.3.1. Study context

The study was conducted in Bavaria (one of the 16 German federal states). In specific, five Bavarian municipalities were selected: Aichach, Bad Neustadt a.d.Saale, Freilassing, Hilpoltstein and Landshut (see *Figure 18*). The focus was on small to medium-sized cities, where the railway station usually plays a bigger role in everyday mobility than in metropolises, which usually have several public transport hubs. The municipalities were chosen as to represent different station typologies in terms of size, passenger numbers and their role in the network. In addition, the willingness of the local authorities to participate was also decisive, as the aim of the project (where this study was part of) was to identify deficits in the pedestrian accessibility of railway stations and to develop concrete measures to improve the situation together with local planners and stakeholders (Pajares et al. 2021). However, this paper focuses solely on the findings in regard to perceived accessibility.

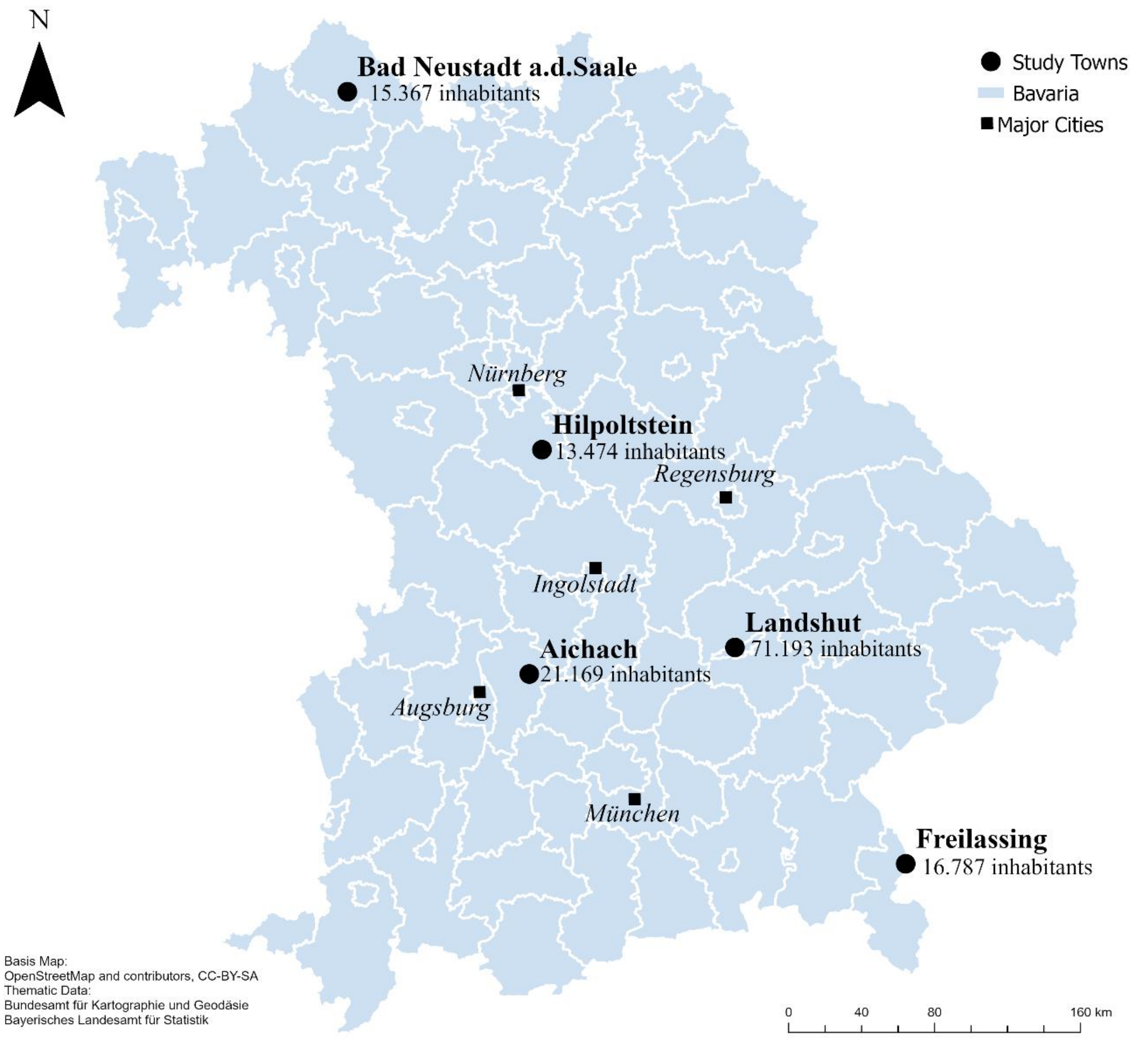


Figure 18: Selected municipalities in Bavaria

In Bavaria, strengthening local public transport, cycling and walking is a central transport policy goal (Bayerische Staatskanzlei 2021). The Bavarian railway infrastructure consists of around 6,500 kilometres of track and 1,066 stations (Bayerisches Staatsministerium für Wohnen, Bau und Verkehr 2021b). But, as shown in *Figure 19,* 59% of all trips in Bavaria are conducted using private motorised vehicles and only 10% of the trips are made using public transport (Nobis and Kuhnimhof 2018). These numbers confirm that in Bavaria public transport in general, and rail transport in particular, are currently not exploited to their full potential.

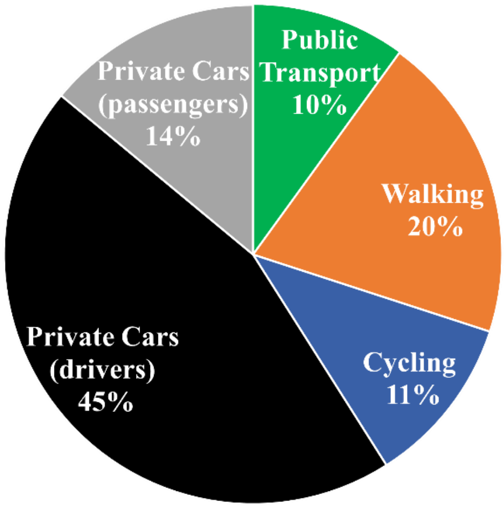


Figure 19: Modal Split in Bavaria (Nobis and Kuhnimhof 2018)

The low mode share of pedestrians and public transport users in Bavaria could be attributed to shortcomings in pedestrian accessibility, as people are less likely to use the train as the distance between home and station increases (Keijer and Rietveld 1999). The location of railway stations in Bavaria is a product of history: many are not located in the pedestrian-oriented city centres but rather in outlying districts that are usually more car-oriented and less densely populated.

5.3.2. Quality criteria

In German as well as international literature, essential quality criteria for pedestrian traffic have been discussed (Alfonzo 2005; Carr, Dunsiger, and Marcus 2010; Lo 2009; Southworth 2005). Based on the literature, six overarching quality criteria to evaluate pedestrian accessibility are defined: Directness, Simplicity, Traffic Safety, Security, Comfort, Built Environment. Each quality criterion was assigned a set of indicators. The resulting quality criteria and their corresponding indicators are listed in *Figure 20*. The indicators were chosen specifically for the use case of access to railway stations.

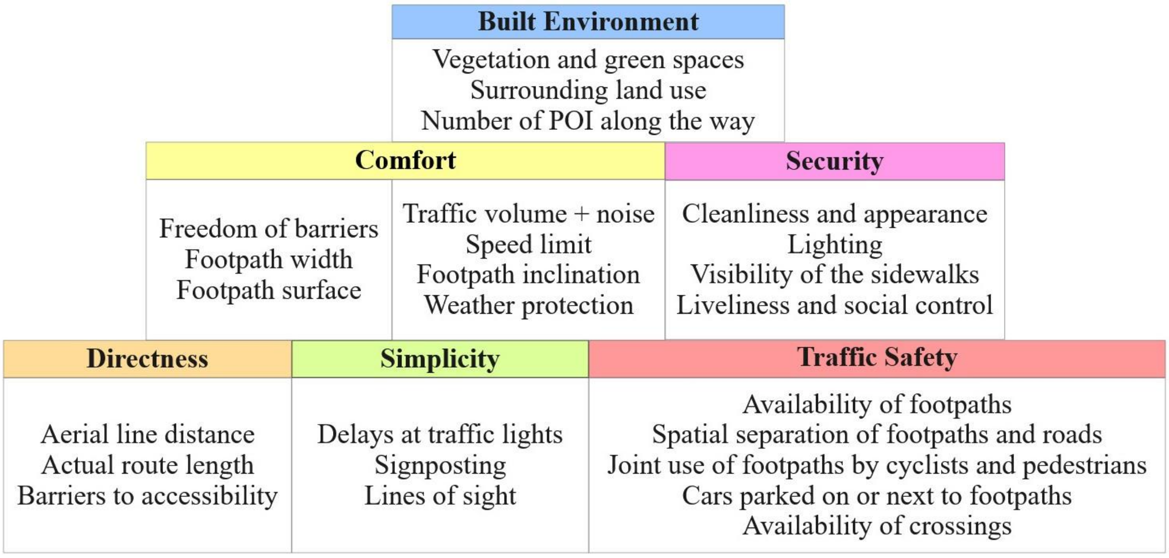


Figure 20: Six quality criteria for pedestrian accessibility, with their respective indicators

The quality criteria, especially comfort and security are significantly influenced by individual perception. Since these cannot be derived directly, the quality criteria are assessed using proxy indicators (e.g. footpath width, lighting). One indicator can have an influence on several quality criteria. For example, the footpath width influences both comfort and traffic safety. The indicators were assigned to the quality criterion for which they are deemed most relevant. The following sub-sections outline the interplay of the chosen quality criteria and their (proxy) indicators.

5.3.2.1. Directness

The directness is primarily dependent on the actual length of the route to the railway station, as opposed to the aerial line distance. To provide direct routes to the population, a high local connectivity (ratio of links and nodes) is needed. Major obstacles in terms of directness, besides badly connected neighbourhoods, are linear barriers such as fences, railway tracks or busy roads that can only be crossed at certain points. The actual length of the route affects how attractive a route is perceived (Handy and Clifton 2001; Lo 2009; Saelens et al. 2003). A comfortable walking distance for the majority of people is around 10 minutes (Calthorpe 1993), which also seems to be valid for trips to train stations (Daniels and Mulley 2013; S. O'Sullivan and Morrall 1996).

5.3.2.2. Simplicity

The simplicity of a route depends, among other things, on the number of roads to be crossed. For pedestrian crossings with traffic lights, the waiting time and the duration of the green phase are deciding factors. In addition, a distinction must be made between automatic light signal systems and light signal systems with manual signal request devices. In addition, means of orientation to and from the railway station are important in terms of simplicity, and especially necessary for people who are not familiar with the area. This can be provided by consistent signposting, which also help to counteract overestimation of walking distances (Ralph et al. 2020). Furthermore, lines of sight towards characteristic buildings in the city can significantly improve orientation in public spaces.

5.3.2.3. Traffic safety

The traffic safety as perceived by pedestrians is determined by the characteristics of the footpath and by the presence of other road users on or near the footpaths. The availability of sidewalks and the spatial buffer between sidewalk and road are therefore important (Kweon et al. 2021). Not only driving cars affect the traffic safety of pedestrians, cyclists on the pavement can also lead to dangerous situations (Mesimäki and Luoma 2021). In addition, parked cars on the street (or even on the walkway) obstruct the visibility of pedestrians (Oxley et al. 1997).

5.3.2.4. Security

How protected pedestrians feel from incidents by other humans and crime depends on the liveliness and social control of an area (Arslan et al. 2018; Saelens et al. 2003). Low visibility of sidewalks, e.g. in underpasses (Hillnhütter 2016) or in areas with dense vegetation (Golan et al. 2019; Lin, Sun, and Li 2015; Wimbardana, Tarigan, and Sagala 2018) or low lighting levels (Saelens et al. 2003; Wimbardana, Tarigan, and Sagala 2018), leads to decreased perceived security, while a lively environment ("eyes on the street" concept) can increase it (Gehl 2013; J. Jacobs 1961). In addition, cleanliness and appearance of the path and the surrounding environment have an impact hereon (Golan et al. 2019; Saelens et al. 2003).

5.3.2.5. Comfort

How comfortable it is to walk on a specific path depends on infrastructural criteria, such as footpath width (Alfonzo 2005), surface (Wimbardana, Tarigan, and Sagala 2018) and guidance (Saelens et al. 2003). Sufficient footpath width is important to ensure comfortable overtaking or crossing of pedestrians. If a footpath leads along a road, footpath width is perceived differently depending on the permitted speed on the road. At high speeds and with high traffic volumes, a spatial separation of road and footpath is therefore vital, also to reduce the noise levels for the pedestrians. If the footpath surface is uneven or contains many potholes, walking on it requires additional attention and may reduce the accessibility for some users. Freedom from barriers is not only of particular importance to people with limited mobility, but also for people with prams or heavy suitcases, for example, to comfortable travel on footpaths (Zakaria and Ujang 2015). In addition, walking comfort is influenced by the inclination (Handy and Clifton

2001) and by the presence of weather protection (e.g. arcades, trees) (Arslan et al. 2018; Pilipenko, Skobeleva, and Bulgakov 2018; Whyte 1980).

5.3.2.6. Built environment

How attractive a footpath and consequently walking in-general is perceived by pedestrians, is largely influenced by the built environment in which the footpath is located (Pushkarev and Zupan 1971; Southworth 2005). For example, a path through a busy city centre with many shops and people is more entertaining than a path through a deserted industrial area or a boring underpass (Hillnhütter 2016). Additionally, city centres provide numerous points of interest (POI) to visit and run errands along the way (Lin, Sun, and Li 2015; Saelens et al. 2003). But not only buildings and people, also natural elements such as street trees and green spaces provide visual and auditory stimuli and have an positive impact on the attractiveness of an area (Golan et al. 2019; Lin, Sun, and Li 2015).

5.3.3. Survey

The locals' knowledge about existing weak points in the footpath network is invaluable. Experiences and feelings while walking can not be assimilated other than asking people frequenting those paths on a regular basis. The perceptions of local rail users were gathered using on-site and online surveys. The surveys were conducted in all five municipalities in autumn 2017. The on-site surveys were conducted directly at the railways stations. Five interviewers spend two days on each of the station and surveyed as many persons as possible within this time. The on-site survey was deliberately kept short due to the often limited time available at the railway station. A purposive sampling approach was used. In order to participate, survey candidates had to be frequent rail users (at least once a month) and non-transfer passengers (the stations surveyed had to be the starting or ending point of the train journey). These criteria were asked right at the beginning of the survey. However, occasional customers and transfer passengers were also given the opportunity to name problem areas that came to their attention. The online survey was published on the project's own website and was advertised by the municipal officials. The following questions were asked in both surveys (on-site and online):

General: As perceived accessibility is difficult to grasp, mode choice and specific survey questions are used as proxy to assess perceived accessibility. First, general information about the survey participants and their travel behaviour was recorded:

- Personal information: Age, gender, employment, place of residence
- Car use: Driver's license, car availability

- Rail use: frequency, destinations, purpose (e.g. work, education, shopping)

Non-Walkers: Then, participants were asked which mode of transport they used to reach the railway station. If respondents stated that they did not walk to the railway station, they were asked:

- Why did you not walk to the railway station?
- Why did you choose the other mode of transport?
- Have you ever walked to the railway station?

Walkers: If respondents stated that they walk to the railway station, they were asked:

- Why did you walk to the railway station?
- What would be the maximum distance you are willing to walk to the railway station?
- What and where are weak points on the way to the railway station and at the railway station itself?

In the online survey, problem areas could directly be pinpoint in a web-based tool. In addition, the participants were asked to rate how important different quality indicators for pedestrian accessibility are to them.

5.3.4. Analysis

For each city, the location-based survey results (starting points, mode of transport to the railway station, reported problem statements) were visualised in a map (see *Section 5.4*). The reported problem statements were matched with the quality criteria and their respective indicators that were found in the literature (see *Section 5.3.2*; e.g. the statement "There is no barrier-free access to platform 7." was matched with *Comfort* → *Freedom of barriers*). The reported problem statements were visualized by the use of a colour schema (Built Environment: blue, Comfort: yellow, Security: pink, Directness: orange, Simplicity: green, Traffic Safety: red). This colour scheme is used throughout the paper to make it easier to read the graphics and understand the connections. In addition, as proposed by Rossetti et al. (2020), travel-time isochrones (contour-based accessibility measure) were calculated for the five assessed train stations, using 10 minutes walking time and a walking speed of 5 km/h, and thus representing the average time that people are willing to walk to places. For the walking path network, OpenStreetMap data was used (OpenStreetMap contributors 2021). The calculated isochrones were intersected with population data from the Census household survey (Statistische Ämter des Bundes und der Länder 2011). Therewith, it was assessed if there is a connection between mode choice, walking distance to the railway station and reported problem areas.

If participants started their trip roughly within the 10 minutes walking distance from the railway station and chose a motorised mode, their survey answers were analysed in more detail to understand why. The mode choice differences between walking and cycling were not assessed, as these two active modes usually complement each other, depending on the total trip (chain) length and personal preferences. The answers to the non-location-based survey questions were summarised in diagrams.

In addition, chi-squared-tests and a logistic regression model were used to explore the differences in mode choice and the reasons therefore between places (cities) and people (gender and age). The software Epi Info 7 (Nieves and Jones 2009) was used therefore. Chi-squared-tests were conducted (see *Table 10*) to test the association between the potential predictors (age group, gender, city) and the dependent variables (modes). Furthermore, a logistic regression model was built for mode choice, reasons to walk and reasons not to walk. Age groups (<18 - children ; 18 to <30 - junior adults ; 30 to <60 - senior adults ; >60 - elderly), gender (female ; male) and municipalities (>20.000 inhabitants - medium ; <20.000 inhabitants - small) were used as other variables (see *Table 11*, *Table 12* and *Table* 13). Children as vulnerable groups were selected as a comparison group for the age groups. The input data were filtered according to the gender and age groups mentioned above.

5.4. Results

A total of 754 valid questionnaires was gathered (537 on-site and 217 online; see *Table 9*). According to the calculation method proposed by Kadam and Bhalerao (2010), 384 or more surveys are needed to represent Bavaria and to have a confidence level of 95% that the real value is within ±5% of the surveyed value – under the precondition that the sample is randomized. However, the cities used different advertisement methods, which leads to an unequal distribution of online survey participants per city. To understand how randomized the survey sample is, the distribution of the participants' age groups and genders is compared to the last Bavarian census (Statistische Ämter des Bundes und der Länder 2011). It reveals that the younger half of survey participants (<30 years) is somewhat over represented in comparison to the census, while the older half of participants (>30 years) is somewhat underrepresented. The reason for this could be that the share of public transport users is also higher among younger people than among older people (Nobis and Kuhnimhof 2018). In addition, a higher proportion of men participated in the online survey. Since the aim of the study is not to make generalised statements for the whole of Bavaria, but rather to explore how certain people perceive the pedestrian accessibility of railway stations, the sample size achieved is considered sufficient for this purpose, even if not all social groups are equally well represented.

Table 9: Number of survey participants and descriptive statistics

Municipality	**Inhabitants**	**# of participants**		
		on-site	**online**	**sum**
Aichach	21,169	121	15	136
Bad Neustadt a.d. Saale	15,367	85	41	126
Freilassing	16,878	115	118	223
Hilpoltstein	13,474	89	8	97
Landshut	71,193	127	35	162
Sum	**137,990**	**537**	**217**	**754**

Age Groups	**Bavaria** (Census 2011)	**% of participants**		
		on-site	**online**	**sum**
<18 (children)	17%	38%	2%	24%
18 to <30 (junior adults)	15%	27%	18%	29%
30 to <60 (senior adults)	49%	27%	57%	34%
>60 (elderly)	19%	8%	23%	10%

Gender	**Bavaria** (Census 2011)	**% of participants**		
		on-site	**online**	**sum**
Male	49%	49%	59%	54%
Female	51%	51%	41%	46%

In the following, the results are aggregated from the responses in the on-site and online surveys. The focus lies on the survey questions concerning walking to and from the station. First, the statistical analyses are presented in *Table 10*, *Table 11*, *Table 12* and *Table 13*, then the results are described by the help of figures.

Table 10: Chi-squared test: People, places and mode choice

		Walking				Cycling			
		total (n = 699) (n (%))	**yes (n = 300)** (n (%))	**no (n = 399)** (n (%))	**X^2-Test p-value**	**total (n = 699)** (n (%))	**yes (n = 126)** (n (%))	**no (n = 573)** (n (%))	**X^2-Test p-value**
Age Group	**< 18 (children)**	159 (22.75%)	91 (30.33%)	68 (17.04%)	**< 0.01**	159 (22.75%)	24 (19.05%)	135 (23.56%)	0.16
	18 to < 30 (junior adults)	211 (30.19%)	76 (25.33%)	135 (33.83%)		211 (30.19%)	42 (33.33%)	169 (29.49%)	
	30 to < 60 (senior adults)	255 (36.48%)	95 (31.67%)	160 (40.10%)		255 (36.48%)	52 (41.27%)	203 (35.43%)	
	> 60 (elderlies)	74 (10.59%)	38 (12.67%)	36 (9.02%)		74 (10.59%)	8 (6.35%)	66 (11.52%)	
Gender	**Female**	332 (47.50%)	142 (47.33%)	190 (47.62%)	0.94	332 (47.50%)	53 (42.06%)	279 (48.69%)	0.18
	Male	367 (52.50%)	158 (52.67%)	209 (52.38%)		367 (52.50%)	73 (57.94%)	294 (51.31%)	
Municipality	**big (> 20.000 inh.)**	271 (38.77%)	79 (26.33%)	192 (48.12%)	**< 0.01**	271 (38.77%)	53 (42.06%)	218 (38.05%)	0.40
	small (< 20.000 inh.)	428 (61.23%)	221 (73.67%)	207 (51.88%)		428 (61.23%)	73 (57.94%)	355 (61.95%)	

		Private Car Driver				Private Car Passenger				Bus			
		total (n = 699) (n (%))	**yes (n = 125)** (n (%))	**no (n = 574)** (n (%))	**X^2-Test p-value**	**total (n = 699)** (n (%))	**yes (n = 58)** (n (%))	**(n = 641)** (n (%))	**X^2-Test p-value**	**total (n = 699)** (n (%))	**yes (n = 90)** (n (%))	**no (n = 609)** (n (%))	**X^2-Test p-value**
Age Group	**< 18 (children)**	159 (22.75%)	2 (1.60%)	157 (27.35%)	**< 0.01**	159 (22.75%)	16 (27.59%)	143 (22.31%)	**0.07**	159 (22.75%)	26 (28.89%)	133 (21.84%)	**0.02**
	18 to < 30 (junior adults)	211 (30.19%)	34 (27.20%)	177 (30.84%)		211 (30.19%)	24 (41.38%)	187 (29.17%)		211 (30.19%)	35 (38.89%)	176 (28.90%)	
	30 to < 60 (senior adults)	255 (36.48%)	71 (56.80%)	184 (32.06%)		255 (36.48%)	14 (24.14%)	241 (37.6%)		255 (36.48%)	23 (25.56%)	232 (38.10%)	
	> 60 (elderlies)	74 (10.59%)	18 (14.40%)	56 (9.76%)		74 (10.59%)	4 (6.90%)	70 (10.92%)		74 (10.59%)	6 (6.67%)	68 (11.17%)	
Gender	**Female**	332 (52.50%)	61 (51.20%)	271 (52.79%)	0.75	367 (52.5%)	28 (48.28%)	339 (52.89%)	0.50	367 (52.5%)	44 (48.89%)	323 (53.04%)	0.46
	Male	367 (47.50%)	64 (48.80%)	303 (47.21%)		332 (47.5%)	30 (51.72%)	302 (47.11%)		332 (47.5%)	46 (51.11%)	286 (46.96%)	
Municipality	**big (> 20.000 inh.)**	271 (38.77%)	55 (44.00%)	216 (37.63%)	0.19	271 (38.77%)	27 (46.55%)	244 (38.07%)	0.20	271 (38.77%)	57 (63.33%)	214 (35.14%)	**> 0.01**
	small (< 20.000 inh.)	428 (61.23%)	70 (56.00%)	358 (62.37%)		428 (61.23%)	31 (53.45%)	397 (61.93%)		428 (61.23%)	33 (36.67%)	395 (64.86%)	

Table 11: Logistic regression: People, places and mode choice

		Walking Odds Ratios (95% C.I.)		**Cycling** Odds Ratios (95% C.I.)	
		Crude	Adjusted Model	Crude	Adjusted Model
Age Group	**(elderly/child)**	0.79 (0.45 - 1.37)	-	0.68 (0.29 - 1.60)	-
	(senior adult/child)	0.44 (0.30 - 0.66)*	0.47 (0.31 - 0.71)*	1.44 (0.85 - 2.45)	-
	(young adult/child)	0.42 (0.28 - 0.64)*	0.49 (0.32 - 0.76)	1.40 (0.81 - 2.42)	-
Gender	**(female/male)**	0.99 (0.73 - 1.33)	-	0.77 (0.52 - 1.13)	-
Municipality	**(small/big)**	2.59 (1.88 - 3.58)*	2.41 (1.73 - 3.36)*	0.85 (0.57 - 1.25)	-

		Private Car Driver Odds Ratios (95% C.I.)		**Private Car Passenger** Odds Ratios (95% C.I.)		**Bus** Odds Ratios (95% C.I.)	
		Crude	Adjusted Model	Crude	Adjusted Model	Crude	Adjusted Model
Age Group	**(elderly/child)**	25.22 (5.67 - 112.15)*	25.22 (5.67 - 112.15)*	0.51 (0.16 - 1.58)	-	0.45 (0.18 - 1.15)	-
	(senior adult/child)	30.28 (7.31 - 125.40)*	30.28 (7.31 - 125.40)*	0.52 (0.25 - 1.10)	-	0.51 (0.28 - 0.92)*	0.44 (0.24 - 0.81)*
	(young adult/child)	15.07 (3.56 - 63.74)*	15.07 (3.56 - 63.74)*	1.15 (0.59 - 2.24)	-	1.02 (0.58 - 1.77)	-
Gender	**(female/male)**	1.07 (0.72 - 1.57)	-	1.20 (0.70 - 2.06)	-	1.18 (0.76 - 1.84)	-
Municipality	**(small/big)**	0.77 (0.52 - 1.14)	-	0.71 (0.41 - 1.21)	-	0.31 (0.20 - 0.50)*	0.31 (0.19 - 0.50)*

* = p-value < 0.05

Table 12: Logistic regression: People, places and reasons not to walk

		Time-consuming		Tedious		Not enough or bad footpaths		Boring	
		Odds Ratios (95% C.I.)		Odds Ratios (95% C.I.)		Odds Ratios (95% C.I.)		Odds Ratios (95% C.I.)	
		Crude	Adjusted Model	Crude	Adjusted Model	Crude	Adjusted Model	Crude	Adjusted Model
Age Group	**(elderly/child)**	0.20 (0.04 - 1.17)	-	3.79 (1.17 - 12.3)*	3.79 (1.17 - 12.3)*	NA	-	0.62 (0.15 - 2.62)	-
	(senior adult/child)	0.20 (0.04 - 0.87)*	0.20 (0.04 - 0.87)*	1.23 (0.59 - 2.58)	-	NA	-	0.72 (0.29 - 1.81)	-
	(young adult/child)	0.40 (0.08 - 1.90)	-	1.26 (0.61 - 2.63)	-	NA	-	1.10 (0.46 - 2.63)	-
Gender	**(female/male)**	1.64 (0.77 - 3.46)	-	1.00 (0.60 - 1.67)	-	0.45 (0.19 - 1.04)	-	0.84 (0.45 - 1.59)	-
Municipality	**(small/medium)**	0.83 (0.40 - 1.71)	-	1.27 (0.76 - 2.11)	-	4.64 (1.81 - 11.09)*	4.64 (1.81 - 11.90)*	0.61 (0.32 - 1.16)	-

		Bad weather		Area not nice		Feeling unsafe (crime)		Feeling unsafe (traffic)	
		Odds Ratios (95% C.I.)		Odds Ratios (95% C.I.)		Odds Ratios (95% C.I.)		Odds Ratios (95% C.I.)	
		Crude	Adjusted Model	Crude	Adjusted Model	Crude	Adjusted Model	Crude	Adjusted Model
Age Group	**(elderly/child)**	0.83 (0.22 - 3.11)	-	5.00 (1.04 - 24.12)*	5 (1.04 - 24.12)*	4.63 (0.69 - 31.05)	-	2.77 (0.50 - 15.49)	-
	(senior adult/child)	1.27 (0.53 - 3.00)	-	2.90 (0.79 - 10.72)	-	3.08 (0.65 - 14.67)	-	1.76 (0.46 - 6.82)	-
	(young adult/child)	1.37 (0.58 - 3.23)	-	1.71 (0.44 - 6.62)	-	5.29 (1.16 - 24.08)*	5.29 (1.16 - 24.08)*	0.80 (0.18 - 3.53)	-
Gender	**(female/male)**	1.14 (0.63 - 2.04)	-	0.64 (0.30 - 1.35)	-	1.67 (0.80 - 3.52)	-	0.63 (0.25 - 1.58)	-
Municipality	**(small/medium)**	0.57 (0.31 - 1.03)	-	1.14 (0.54 - 2.39)	-	1.64 (0.78 - 3.44)	-	1.48 (0.60 - 3.67)	-

* = p-value < 0.05
NA = not enough data

Table 13: Logistic regression: People, places and reasons to walk

		Free of charge		Fast		No alternative	
		Odds Ratios (95% C.I.)		Odds Ratios (95% C.I.)		Odds Ratios (95% C.I.)	
		Crude	Adjusted Model	Crude	Adjusted Model	Crude	Adjusted Model
Age Group	**(elderly/child)**	1.38 (0.60 - 3.17)	-	0.29 (0.10 - 0.80)*	0.29 (0.10 - 0.82)*	0.41 (0.17 - 0.98)*	0.41 (0.17 - 1.00)*
	(senior adult/child)	0.98 (0.52 - 1.82)	-	0.61 (0.25 - 1.46)	-	0.47 (0.25 - 0.89)*	0.51 (0.26 - 0.97)*
	(young adult/child)	1.24 (0.65 - 2.36)	-	0.31 (0.14 - 0.71)*	0.38 (0.16 - 0.89)*	0.39 (0.20 - 0.75)*	0.44 (0.23 - 0.88)*
Gender	**(female/male)**	0.89 (0.55 - 1.46)	-	1.06 (0.58 - 1.92)	-	1.15 (0.70 - 1.88)	-
Municipality	**(small/medium)**	1.28 (0.75 - 2.21)	-	2.71 (1.46 - 5.05)*	2.49 (1.31 - 4.74)*	2.18 (1.22 - 3.88)*	1.95 (1.07 - 3.53)*

		Enjoy walking		Nice area		Form of exercise		While running errands	
		Odds Ratios (95% C.I.)		Odds Ratios (95% C.I.)		Odds Ratios (95% C.I.)		Odds Ratios (95% C.I.)	
		Crude	Adjusted Model	Crude	Adjusted Model	Crude	Adjusted Model	Crude	Adjusted Model
Age Group	**(elderly/child)**	3.10 (1.06 - 9.08)*	3.10 (1.06 - 9.08)*	1.49 (0.57 - 3.90)	-	3.63 (1.42 - 9.28)*	3.63 (1.42 - 9.28)*	1.16 (0.47 - 2.90)	-
	(senior adult/child)	2.53 (1.25 - 5.13)*	2.53 (1.25 - 5.13)*	0.41 (0.21 - 0.80)*	0.47 (0.24 - 0.93)*	2.96 (1.52 - 5.79)*	2.96 (1.52 - 5.79)*	0.58 (0.30 - 1.09)	-
	(young adult/child)	1.14 (0.58 - 2.23)	-	0.42 (0.21 - 0.82)*	0.45 (0.23 - 0.90)*	1.18 (0.61 - 2.29)	-	0.73 (0.37 - 1.41)	-
Gender	**(female/male)**	1.10 (0.64 - 1.88)	-	2.44 (1.45 - 4.11)*	2.27 (1.32 - 3.88)*	0.92 (0.56 - 1.53)	-	1.29 (0.78 - 2.14)	-
Municipality	**(small/medium)**	1.01 (0.56 - 1.81)	-	0.99 (0.57 - 1.74)	-	0.88 (0.51 - 1.53)	-	0.59 (0.91 - 2.77)	-

* = p-value < 0.05

In four of the five municipalities surveyed, walking is the most important mode of transport to reach the station and was used by 41% of respondents in total. *Figure 21* shows all modes of transport used on the way to the railway station as an average for all five municipalities. A quarter of the surveyed rail users arrive at the station by car. The high proportion of car passengers (not drivers) is particularly striking. Notably, more rail users arrive to the station by bicycle than by public transport. However, it was not investigated separately to what extent this is connected to the local public transport (bus) offer and coordination of the timetables. It can be assumed that a better bus service would also result in a higher proportion of bus users. A small share of 3% uses “other” modes such as taxis or scooters.

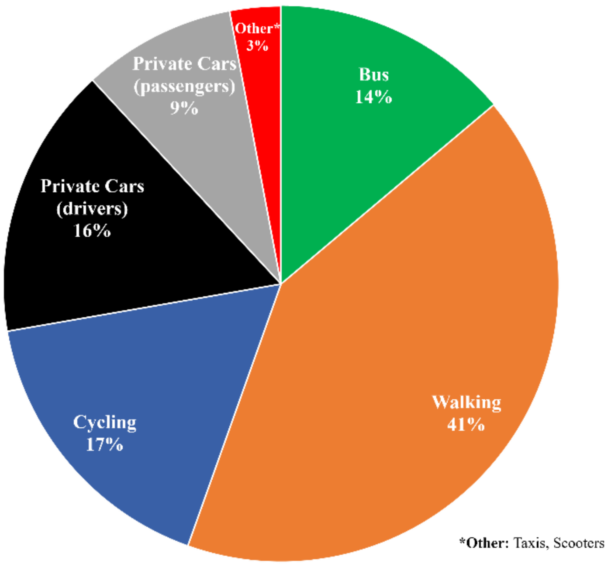


Figure 21: Modes of transportation used to reach railway stations

In the following, the factors influencing perceived pedestrian accessibility are presented, each as a summary of all five model municipalities.

5.4.1. Place

The share of pedestrians (and the overall modal split) depends on how big the town is and where its railway station is located. Although the journey to the station is predominantly made on foot, the composition of the mode of transport choice varies greatly in the five cities studied (see *Figure 22*). The statistical analyses (see *Table 10* and *Table 11*) show that the city size has an influence on the mode choice on the way to the railway station. In small towns, people are 2.41 times more likely to walk because ‘it is fast’ and they have no alternative (presumably because of the lack of bus connections). In the medium-sized cities, people are 3.22 times more likely to travel by bus.

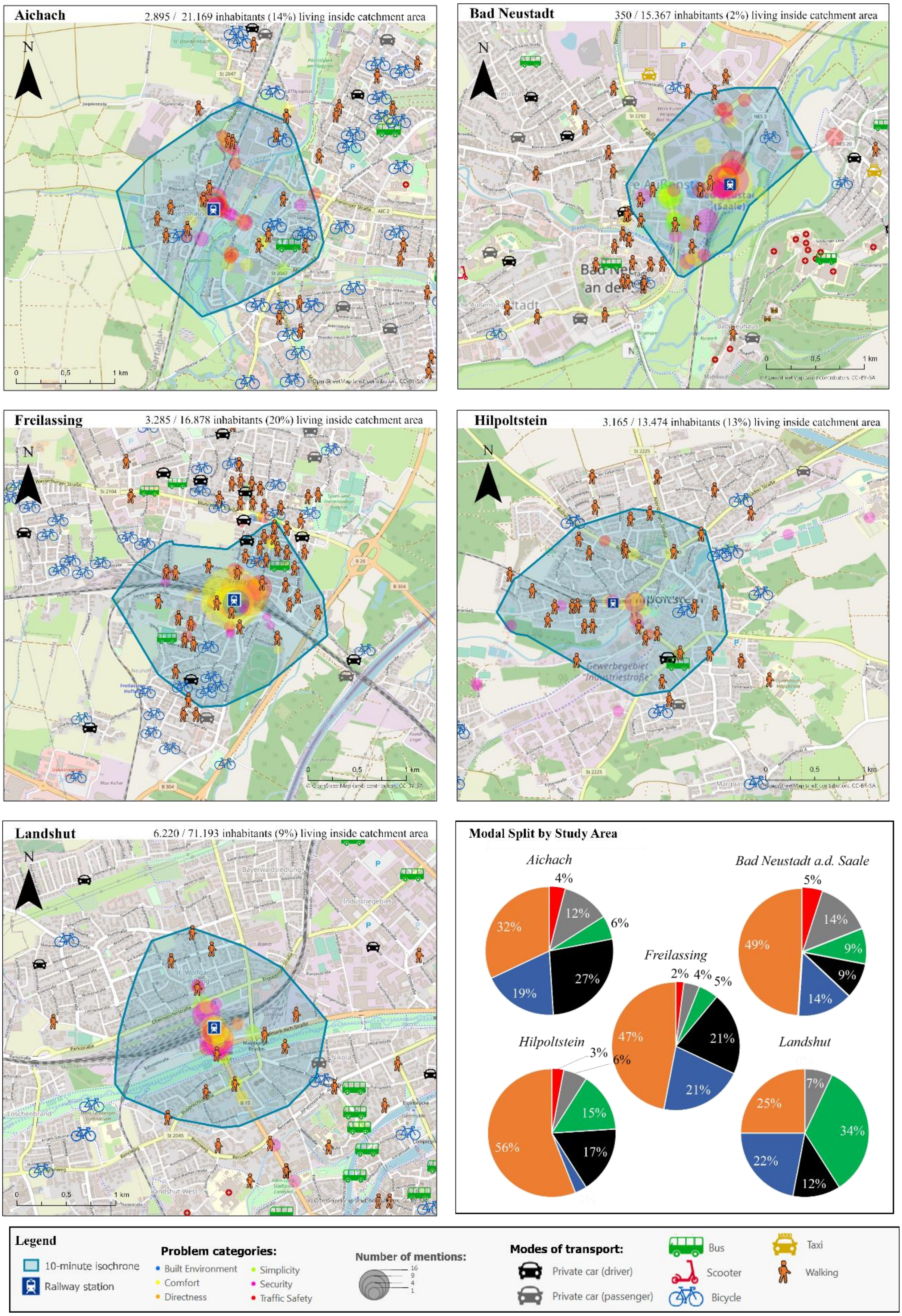


Figure 22: Catchment areas, starting points, reported problem areas and mode shares for all study areas

Smaller towns with central train stations, such as Hilpoltstein and Freilassing, demonstrate very high proportions of pedestrians (56% and 47%). Larger cities such as Landshut, where only a low share of the total population lives within the 10 minute walking catchment area of the railway station, have a lower proportion of pedestrians. This is due to the longer distance that would need to be travelled by foot in order to reach the station. Places such as Aichach, on the other hand, have a large share of rail users that travel to the station by car for the comparatively small size of the town. This may be due to the relatively large free P+R facility with 186 parking spaces (BEG 2019). Similarly, cities with well-developed B+R facilities, such as Aichach with 168 or Freilassing with 373 bicycle parking spaces, have a higher proportion of cyclists than Bad Neustadt with only 68 bicycle parking spaces (BEG 2019). This indicates that there is a direct correlation between provided infrastructure and mode choice. Accordingly, it can be assumed that a good walking infrastructure also leads to more pedestrians – or the other way around. In Bad Neustadt, the train station is located next to an industrial area. Thus, only 2% of the population lives within the catchment area. Anyhow, Bad Neustadt has a high share of pedestrians – this may be due to a high proportion of pupils and workers that are commuting to the nearby industrial sites and school campuses.

Figure 23 shows how much time the respondents need to get to the railway station by their chosen means of transport. More than 50% of the respondents need 5-15 minutes to get to the station, 25% less than 5 minutes and only 2% more than 30 minutes. Journeys of more than 15 minutes are mainly made by bus or car, while 84% of the walking trips were not longer than 15 minutes – which roughly aligns with the numbers found in the literature (see *Section 5.2.1*). But it is noticeable that also many short distances, that could probably have been covered by bicycle or on foot, were travelled by car.

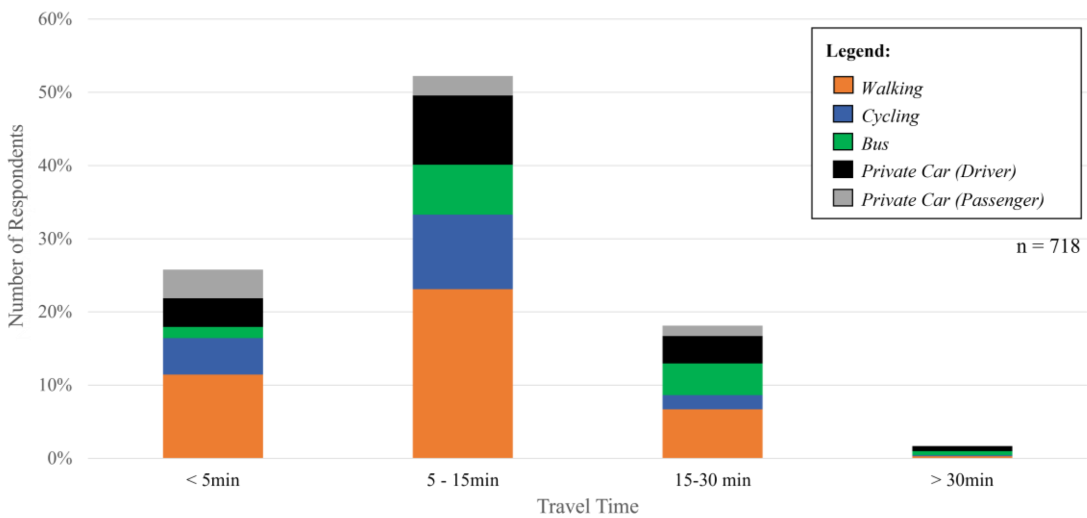
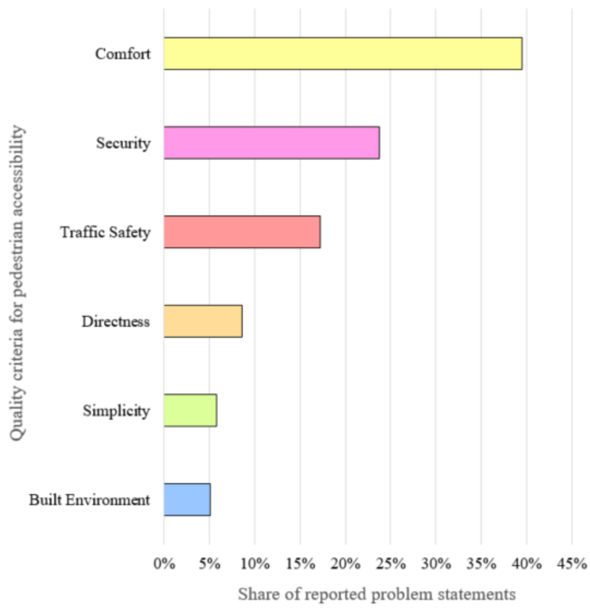


Figure 23: Travel time required to reach the station, aggregated by mode

In order to understand the connections between mode choice and the characteristics of the place, *Figure 22* shows all starting points and the respective mode used on the way to the railway station. In addition, the reported problem statements are highlighted. The colour of the circle indicates criteria to which the statement refers (based on *Figure 20*), and the size of the circle indicates the number of respondents who mentioned this problem. In total, 860 point-based weaknesses were reported by the participants. The distribution of the problems mentioned per criterion and indicator are summarised in *Figure 24*. Many of the weak points are directly located at or in front of the railway station. Especially freedom from barriers was a particular problem at four out of five stations, mentioned not only by elderly respondents but by the whole population. This result is not surprising, as currently only 492 of the 1,066 stations in Bavaria are barrier-free (Bayerisches Staatsministerium für Wohnen, Bau und Verkehr 2021a). Other common issues on the way to and at the railway station were related to security (e.g. dirty appearance of the station, unpleasant underpasses, lack of lighting) and traffic safety (mainly absence of road crossings). For some indicator categories, e.g. “incline” and “visibility of the sidewalk”, no point weaknesses were reported. Interestingly, inadequate or bad footpaths are a significantly more common problem in small towns than in bigger cities.



Comfort	Freedom from barriers	31.9%
	Footpath width	2.9%
	Footpath surface	1.7%
	Traffic volume + noise	1.5%
	Weather protection	1.0%
	Speed limit	0.5%
	Footpath inclination	0.0%
Security	Cleanliness and appearance	9.9%
	Lighting	8.8%
	Liveliness and social control	5.0%
	Visibility of the sidewalks	0.0%
Traffic Safety	Availability of crossings	11.9%
	Availability of footpaths	2.2%
	Joint use of footpaths by cyclists and pedestrians	2.1%
	Cars parks on or next to footpaths	0.6%
	Spatial separation of footpaths and roads	0.5%
Directness	Barriers to accessibility	8.6%
	Aerial line distance	0.0%
	Actual route length	0.0%
Simplicity	Delays at traffic lights	4.5%
	Signposting	1.2%
	Lines of sight	0.1%
Built Environment	Surrounding land use	4.2%
	Vegetation and green spaces	0.7%
	Points-of-Interest along the way	0.2%

n = 860

Figure 24: Reported problem statements, clustered by categories

5.4.2. People

Pedestrians are predominantly found among senior citizens and schoolchildren. *Figure 25* shows the chosen mode of transport in relation to the age of the respondents. Children and elderly have the largest share of walking, while the car and the bicycle are most frequently used by adults. Younger people are the most frequent bus users, and the proportion of bus users decreases steadily with increasing age. Senior adults are 2.27 times less likely to take the bus than children. Between the different gender, mode choice was equally distributed. The only noticeable difference was that men have chosen the bike more often (19%; in contrast to 15% for women; but not significant). Whereas women used the other modes slightly more often. Comparable age- and gender-specific differences were also found in the Germany-wide MiD study (Nobis and Kuhnimhof 2018).

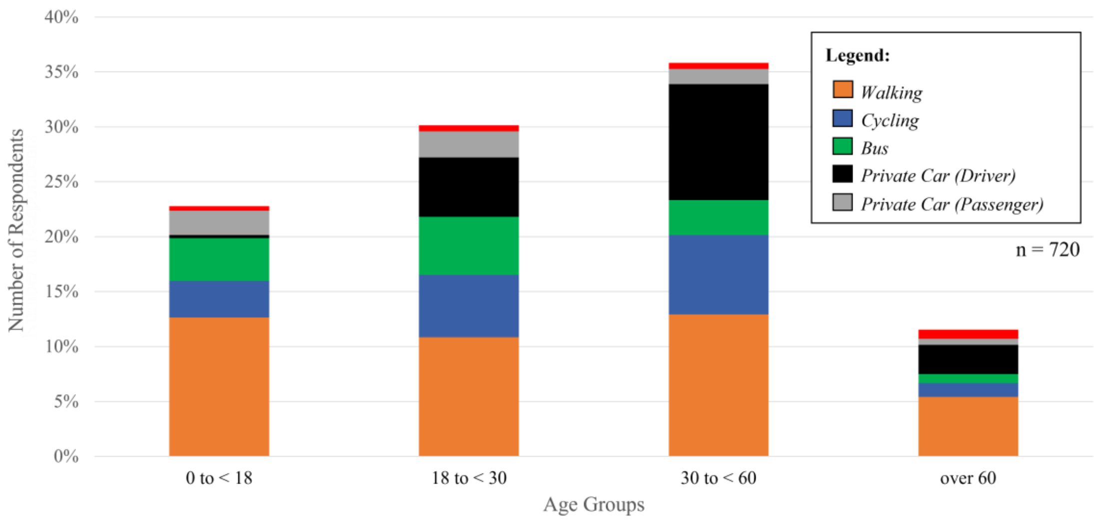


Figure 25: Mode of transport to railway station, by age

When asked about the maximum time people are willing to walk to the station, 40% answered “up to 15 minutes” and another 49% “up to 30 minutes”. The remaining 11% are even willing to walk more than 30 minutes. The discrepancy between the theoretical willingness to walk and the times actually walked suggests that other factors have an influence on this. The assessment reveals that specific point weaknesses, such as poor lighting or unsafe road crossings, present bigger obstacles to perceived pedestrian accessibility than general network connectivity. Comfort, security and safety thus affect route as well as mode choice, for instance some persons claimed to not walk at night due to insufficient street lighting. In this regard, shortcomings were identified in all municipalities surveyed.

Figure 26 summarises how respondents rated different criteria for walking, with each respondent able to select up to five criteria. Sufficient street lighting at night was rated most important for walking, followed by good street crossings and weatherproof paths (shady in summer, good winter service in winter). Other factors considered important were wide and continuous footpaths, relatively slow moving cars on the route and the presence of other people. The resulting importance of the individual criteria largely corresponds to the proportions of the reported problems. Comfort and security seem to be the most important issues, while the built environment only plays a subordinate role. Directness was not asked about, as we consider this criterion to be rather measured than perceived.

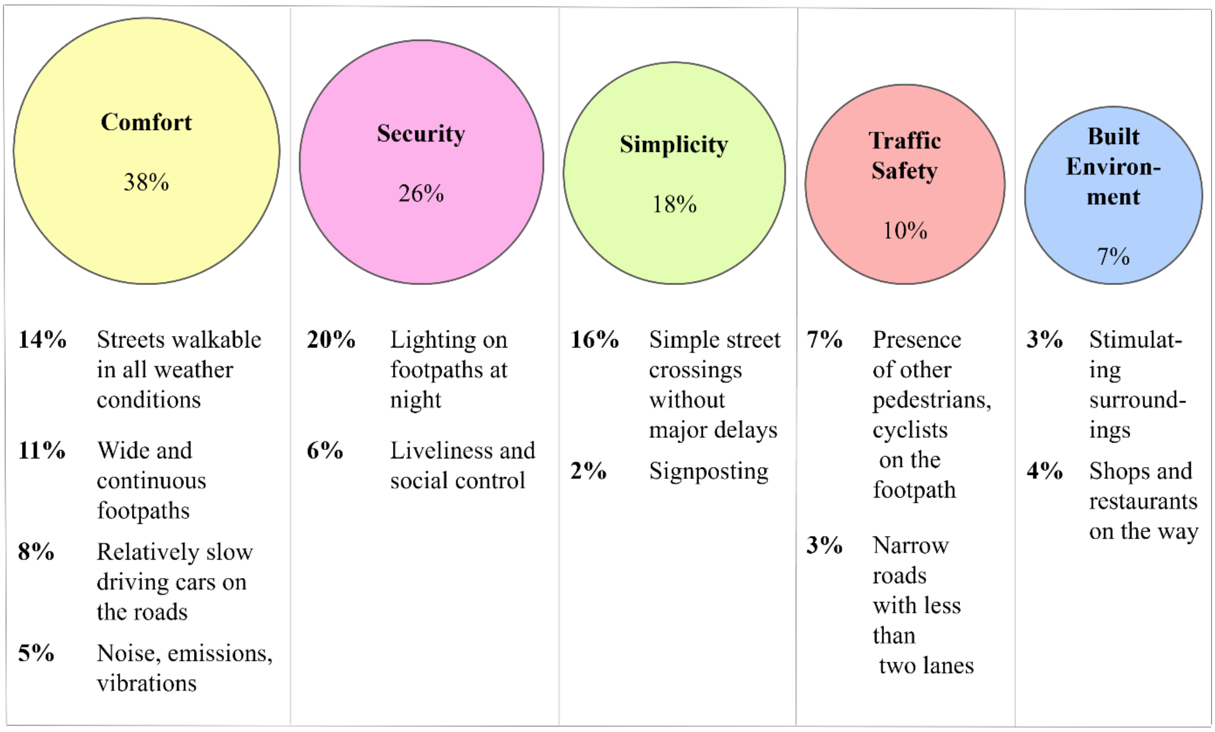


Figure 26: Prioritisation of pedestrian accessibility criteria

It can clearly be seen that different survey participants perceived the same place differently. Different people have different thresholds of how far they are willing to walk, but also different perceptions of comfort, security and safety. This varies especially due to personal characteristics and individual needs, e.g. mobility-impairedness due to disabilities or heavy suitcases.

Figure 27 summarises the answers of all survey participants who said they do not walk to the station to the questions about the reason therefore. For this purpose, the respondents could affirm or deny various given statements. Time constraints and tediousness were the main reasons given for choosing not to walk to the railway stations. Around half of the respondents that came by car stated that the distance was too far to walk or cycle (in their specific situation). Thus, mode choice is clearly dependent on the route length. For older adults in particular, time is a significantly greater barrier to walking than it is for children (see *Table 11*). Respectively, elderly are 3.79 times more likely than children not to walk due to tediousness.

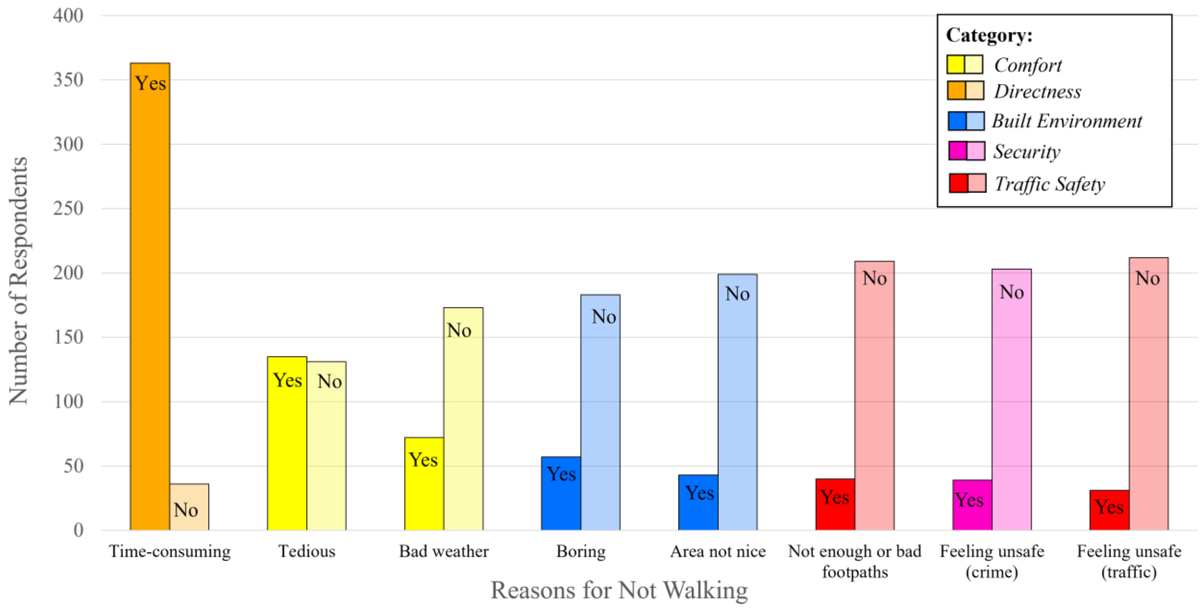


Figure 27: Reasons why people do not walk to the railway station

But noticeably, the distance does not always determine whether a journey to a railway station is made by car, bicycle or by foot. Also bad weather, boredom, unpleasant areas, unsafe feeling as well as missing or bad footpaths discouraged people from walking – reasons, that are related to comfort, built environment and safety. While unpleasant areas are a barrier especially for older people, young adults are significantly more likely to feel unsafe in terms of crime.

Equally, the reasons why 42% of rail users walk to the station are considered. *Figure 28* shows the questions asked and the corresponding answers. Most respondents walk because it is fast, which is related to the directness. Some participants also see walking as a form of exercise, walk because they enjoy it or simply because they have no (affordable) alternative. Those are reasons, that are not directly linked to the quality criteria but are rather individual conditions and characteristics. Others like the nice area or walk for practical reasons, as they run errands or do activities on the way. Those are linked to the built environment. Interestingly, the built environment seems to be an important factor for mode choice although in terms of pedestrian accessibility, built environment received the lowest priority score. Senior adults and elderly significantly more often walk because they enjoy it and see it as a form of exercise than children (see *Table 12*). Respectively, young and senior adults walk more often because of the nice area. Same is true for women.

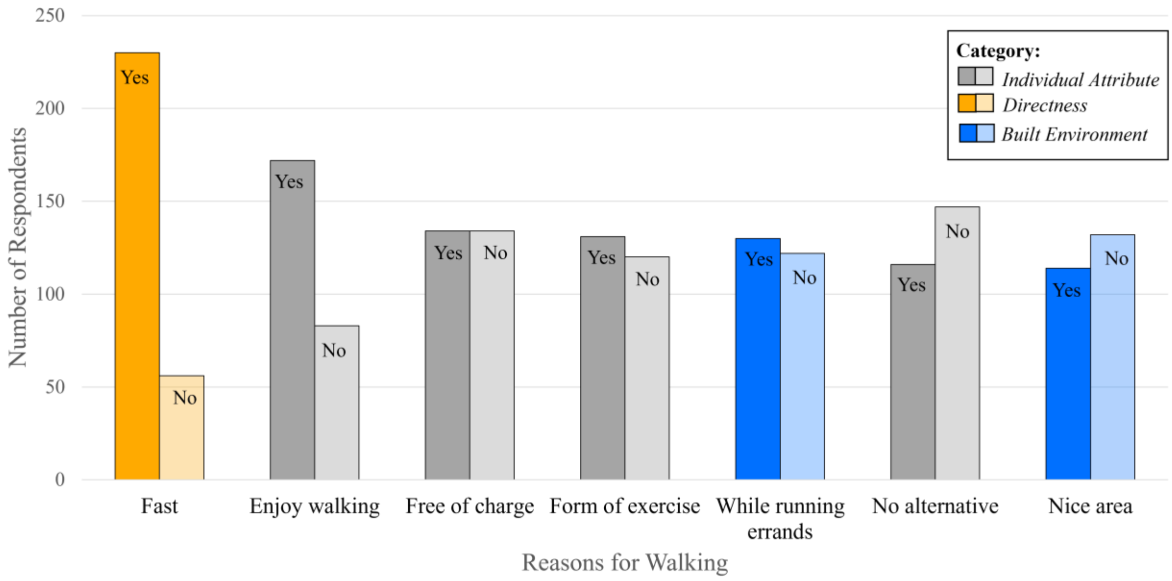


Figure 28: Reasons why people walk to the railway station

5.4.3. Individual utilities: Connection of place and people

In order to better understand how individual utilities are affected by the place and the peoples' characteristics, the survey results of individual persons whose mode choice is particularly intriguing, was analysed in depth.

Two persons who started their trip roughly within a 15 minutes walking distance from the train station in Bad Neustadt arrived by taxi. The reason therefor was the carrying of luggage and bad bus connections. But also respondents who started their trip within walking or cycling distance and do not carry heavy luggage use the car or bus for convenience, like one participant in Aichach. In addition, physical limitations (disabilities, illness) hinder people from walking. For example, two persons in Freilassing came to the station by car because they accompanied mobility-impaired persons.

Other reasons for car use were fear of the dark, fear of bike theft or fear of crime in general. For example, one person that lives 10 walking minutes away from Landshuts' station was brought by car as he was afraid of crime. Same applies to one person in Freilassing that preferred the bus therefore.

Some respondents also stated that they walk or cycle primarily when the weather is good, while in bad weather they choose the bus or the car. In some cases also a combination of several reasons can be found, e.g. in Bad Neustadt one person was driving to the station by car due to time, carrying luggage and a baby stroller and in addition, due to bad weather conditions. It is not known whether the omission of one of these criteria would have already resulted in a mode choice change.

Three participants that started their trip roughly within the 10-minute catchment area (two in Hilpoltstein, one in Bad Neustadt and one in Freilassing) have chosen a motorised mode due to bad walking infrastructure, unpleasant route and/or boredom. Interestingly, the two participants from Hilpoltstein started from almost the same place. The route from this starting point to the station was reported by many participants to be unpleasant. Same applies for the routes from the starting points in Bad Neustadt and Freilassing, where bad walking conditions were pinpointed by many other participants. The routes in Bad Neustadt and Hilpoltstein run along busy roads and through monotonous environments which may cause the unpleasant feeling and boredom of the people due to a lack of visual stimuli. The route in Freilassing leads through an car-oriented commercial area with a reported lack of pedestrian infrastructure (missing paths and too few crossing possibilities).

5.5. Discussion

Within this study, several factors influencing walking were assessed by asking different survey questions. As perceived accessibility can not directly be evaluated, a variety of proxies (mode choice, reasons therefore, rating of pedestrian accessibility criteria, problem statements) were used. Although the answers to most questions show a clear direction for the importance of the six quality criteria, no absolute ranking for the importance of each single factor can be established. The results obtained were very much dependent on the questions asked, which reveals the real problem in this regard: How can we assess perceived accessibility? What question do we need to ask people to find out which factors are the most important? Is there even a universal answer to this, or does perceived accessibility depend primarily on individual capabilities and local external factors? And is there such a thing as the most important factor or is it more about the interactions as a whole?

Due to these still remaining open questions, the authors are aware that this exploratory study does not allow final conclusions to be drawn about the factors influencing perceived pedestrian accessibility to railway stations (in Bavaria), but it does reinforce the assumption (see *Section 5.2.5*) that these are largely dependent on people and places (although five different cities were studied here, it is to be expected that further differences will emerge if the study is extended to other places). Anyhow, the comparison of the different questions allows to get a better understanding of the approximate importance of each factor. Factors that were mentioned repeatedly across different questions suggest that they are among the most important. The mismatch between calculated and perceived pedestrian accessibility (Curl, Nelson, and Anable 2015; Damurski, Pluta, and Zipser 2020; Gebel et al. 2011; Lättman, Olsson, and Friman 2018; McCormack et al. 2008; Pot, van Wee, and Tillema 2021; J. Ryan and Pereira 2021; M. Ryan et al. 2016) and the importance of perception in choosing walking as a mode to walk to the railway station (Gehl 1987; Páez et al. 2020; Pueboobpaphan, Pueboobpaphan, and Sukhotra 2022) could also be confirmed.

Accessibility deficits were identified in all municipalities surveyed, indicating a need for action in this field. This section discusses the identified shortcomings and how these can be addressed by future accessibility studies and tackled by the planning practice.

5.5.1. Time-based factors as prerequisites for walking

Survey participants named time as the most important factor for deciding if they walk or not. Similar to Sarker, Mailer, and Sikder (2019), it was found that especially the senior adults are more sensitive to time-consumption. Thus, direct and simple walking path networks are prerequisites for walking, although connectivity was rarely mentioned as an concrete issue. The reason for this may also be that simple punctual shortcomings (e.g. unpleasant underpasses, missing street lamps) are easy to grasp while the identification of connectivity issues requires a detailed geographical understanding of the area – and may not be something that participants except to be addressed easily.

But even the best walking path network may not be sufficient if the railway station is located in the 'wrong' place and thus not accessible within an appropriate walking time (which, surprisingly, is even up to 30 minutes for the majority of survey participants – in contrast to the findings of Calthorpe (1993), S. O'Sullivan and Morrall (1996) and Daniels and Mulley (2013); this high willingness may be due to the lack of alternative transport options, especially in the smaller towns). The size of the town and the centrality of its railway station determine the length, directness and simplicity of its pedestrian routes. A historical obstruction to pedestrian accessibility that remains is the location of many railway stations outside of city centres (see *Section 5.3.1*), at least in Bavaria.

The solution to this problem is twofold. On the transportation side, supplying attractive pedestrian infrastructure can entice people to travel longer distances by foot (Pueboobpaphan, Pueboobpaphan, and Sukhotra 2022). On the land use side, redeveloping the area around the railway station to include more residential and commercial buildings can bring the origins/destinations closer to the station and therewith shorten travel times. Previous research shows that the more people living and working in close proximity to transit, the more likely it is that they will use the service (Hillnhütter 2016; Murray et al. 1998; Wenner et al. 2020).

As travel time is paramount, combination of both – building attractive transport infrastructure in the shorter term and redeveloping land in the vicinity of the railway station in the longer term – seems advisable.

5.5.2. The underestimated role of comfort

However, how time is perceived depends on safety, comfort and environmental aesthetic levels. These results are in line with Pueboobpaphan, Pueboobpaphan, and Sukhotra (2022) who found that pleasant surroundings can increase the willingness to walk. Similarly, areas that are not attractive discourage people from walking. Especially comfort was given a high priority by the survey participants. This result strengthens the certainty that pedestrian accessibility is strongly connected to perceived quality levels of land use and transport (Arslan et al. 2018; Gkavra et al. 2019; Liang and Cao 2019) but also shows differences to previous studies conducted in India (Bivina, Gupta, and Parida 2019; Gupta, Bivina, and Parida 2022), in which safety and security were identified as the most influential factors. This may be due to the different spatial contexts, which bring with them different conditions in terms of safety and security. In comparison to India, safety and security may be less bigger issues in Bavaria. This assumption would confirm the hypothesis framework set up in *Figure 20* that sees directness, simplicity and traffic safety as the preconditions for walking. If these prerequisites are fulfilled, comfort and safety are decisive for the attractiveness and perception of the path, with greater attractiveness increasing the willingness to walk - and the built environment as the cherry on the top of the cake.

The calculated catchment areas of 10 minutes thus do not really “catch” the perceived walking conditions. Reported point weaknesses and thus perceived obstacles were primarily comfort and safety factors. In addition, the common destinations/origins of all railway users – the train stations – seam to have severe weaknesses in terms of comfort and security themselves (whereby the comfort issues were mainly caused by the fact that the railway stations are not barrier-free) and are thus mayor bottlenecks in terms of perceived accessibility that could be addressed easily by planning practice. In Bavaria, the issue of the non-barrier-free stations is well known and has been tackled since some years. In this course, also the station of Freilassing was rebuilt in 2021. Therewith, the main obstacle identified in 2017 is now solved. Nevertheless, at this point in time, there are still 492 stations that are not barrier-free and represent a major obstacle in accessing the railway system – not just for the people that walk to the station but for everyone.

For some indicators, e.g. “visibility of the sidewalk”, not a single punctual weakness was reported in the five study areas, although this factor was stated to be important in previous studies (Gehl 2013; Golan et al. 2019; Hillnhütter 2016; J. Jacobs 1961; Lin, Sun, and Li 2015; Saelens et al. 2003; Wimbardana, Tarigan, and Sagala 2018). In these cases, the imprecise phrasing chosen by the participants made it difficult for the authors to assign the statement to these specific quality criteria. For example, many participants reported “unpleasant underpasses”. Such a general statement does not allow inferring causation between unpleasantness and dirt or aesthetics. For some people the unpleasantness might also not be linked to a specific feature of the underpass. Those statements were thus categorised as “cleanliness and appearance”. These overlaps and difficulties in delimitation illustrate the ambiguity of transitions between the individual indicators, which often cannot be examined individually but only in connection with other indicators.

In addition, there is a discrepancy between what people stated as their priorities and what they report as problem points in their town. This may be due to the specific local conditions (e.g. the assessed study areas were all topographically flat). Other cities with other walking path networks and other surroundings would certainly generate different punctual weaknesses, as other studies found e.g. that walking in a hilly environment is perceived as barrier (McGinn et al. 2007; Sun et al. 2015). Therefore, a more large-scale study with a wider variety of cities would be needed to validate the results.

Nevertheless, it is clear that perceived factors are of particular importance and should ideally be taken into account when performing accessibility analysis (e.g. by adding them as a generalised cost item to the accessibility formula). There are more criteria that influence pedestrian accessibility but are not mentioned here (e.g. presence of benches (Alfonzo 2005; Arslan et al. 2018; Hillnhütter 2016; Whyte 1980) and aesthetics of building facades (Cervero and Kockelman 1997; Hillnhütter 2016; Lin, Sun, and Li 2015; Lo 2009; Speck 2013)). Further studies are needed to obtain a comprehensive picture.

5.5.3. Travellers’ differing needs and abilities

Mode choice of the participants was not only dependent on the local situation but also very much on the individual characteristics and situations (e.g. age, abilities, carriage of luggage), with age having the strongest influence. Based on the personal situation, in combination with the personal preferences and needs (e.g. in terms of comfort, safety), every person makes its own personal decision on mode choice. Elderly, for example, perceive walking more often as tedious than children, which can be clearly linked to the physical abilities that are changing in the course of ones life. Referring to the capability-approach this means that the internal factors of elderly are not matching with the external factors, which causes this feeling of tediousness. For example, if benches were placed along the path to the station, older people could rest at regular intervals, which would probably make the walk less tedious. Thus, these personal characteristics should be taken into account when making statements of how accessible a place is for certain people (Litman 2003; J. Ryan, Wretstrand, and Schmidt 2019) – and consequently also be reflected in planning practice. As Clifton, Livi Smith, and Rodriguez (2007) and Bivina, Gupta, and Manoranjan (2020) have pointed out, this also requires a greater focus on micro-features in order to fully understand the needs of individual people and take them into account in the urban setting.

The fact that pedestrians (on the way to the railway station) were in our study case predominantly found among senior citizens and schoolchildren indicates that it could make sense to customise future accessibility analysis according to different user groups and their specific needs. As train stations are important services of general interest, it is particularly important to ensure access for all, which is in line with the individual component of accessibility.

5.5.4. Temporal and external factors add further complexity

External factors (e.g. weather, time of the day) were stated to have an impact on perceived accessibility, anyhow, only a few studies can be found that took the accessibility effects of nighttime (Chandra, Jimenez, and Radhakrishnan 2017; Jehle 2020) or weather (Erath et al. 2015) into account. These factors are hard to change by planning practice, but can be mitigated through adapted infrastructure (e.g. weather protection, street lamps) and maintenance (e.g. winter service). In accessibility research and application, more attention should be given to external conditions and the temporal component, as lighting at night and weather conditions were among the most important factors for pedestrian accessibility. Thus, perceived accessibility by night and rain can highly differ from perceived accessibility by day and sunshine.

5.6. Conclusion

This work aimed to understand which factors influence perceived pedestrian accessibility to railway stations and how this may differ for different people and places. It was found that factors related to comfort, traffic safety and security (such as freedom from barriers, availability of street crossings and lighting) are perceived as the most important in terms of pedestrian accessibility. In addition, pedestrian's age as well as the city's size also have a significant influence whether people walk to the railway station or not. With regard to gender, only minor differences were found. *Figure 29* combines the main findings of this study and highlights the factors influencing perceived pedestrian accessibility to railway stations that were identified as the most important ones. Although the importance of several perception factors was determined through various survey questions, these results do not allow quantifying to what extent a specific indicator influences accessibility. But they help in understanding which factors are perceived as important, contribute to the ongoing research on perceived pedestrian accessibility and show where further studies are needed to obtain a more comprehensive picture.

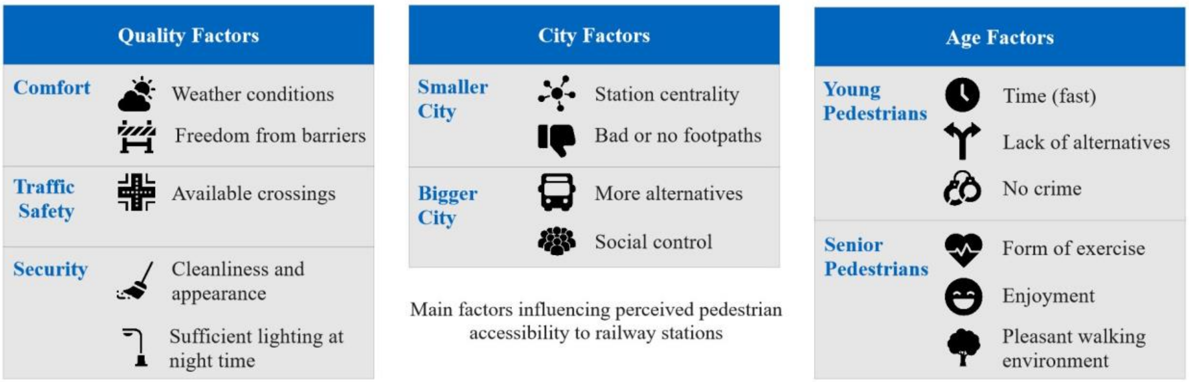


Figure 29: Main identified factors influencing perceived pedestrian accessibility

Interestingly, the biggest weaknesses in perceived accessibility to railway stations are found on the stations themselves. But even punctual micro-feature weaknesses such as a broken street light or an unpleasant underpass on a factually short and safe route discourage people from walking to the station. At the same time, it was also found that many people (especially children) are willing to walk long distances to reach the railway station, mostly because they do not have an alternative. So they also accept weaknesses along the way. Older people, on the other hand, care more about the attractiveness of the environment, walk because they enjoy it and see it as a form of exercise, but they also often find it tedious.

The results of the case studies reveal that different people have different needs and abilities based on age, luggage, daytime and weather conditions. These individualities need to be taken into account through people-centred planning in order to provide access to public transport for all. In particular, we see a need for further research into the needs of different user groups. The capability approach can help to assess whether internal and external factors match. In addition, further research in other contexts is needed in order to understand the differences between different places.

The important comfort, safety and individual factors are currently only represented in a few accessibility analyses, which leads to a discrepancy between calculated and perceived pedestrian accessibility. In future, more importance should be attributed to perceived accessibility – of railway stations but also of other destinations. Pedestrian accessibility measures should be enriched by adding an impedance factor for the attractiveness of the route, reflecting the qualities of the paths, trip experience and personal needs. However, to identify the most important quality criteria of pedestrian accessibility and their individual weighing is still a remaining challenge, which may not be possible to solve universally. Ones the crucial factors are found, they can be assessed by the use of proxy indicators. Most of them can be measured or captured objectively (e.g. footpath width, surface, lighting) and then be translated into a quantitative point schema (e.g. no lighting = 0 points; perfect lighting = 100 points). By multiplying the indicators with weights according to their individual importance and then summing them up, an overall attractiveness score can be derived for each path segment. This score can then serve as an impedance factor and be added to the accessibility formula. Ideally, different impedance factors are determined for different user groups, day times and places. However, detailed data on the walking path network and the whole environment are needed therefore. In addition, some indicators (e.g. appearance) may be not ‘objectively’ measurable. In order to capture those and also to evaluate local context-specific situations and include the individual perceptions of single persons, it seems inevitable to enrich the accessibility analysis by qualitative methods that focus on user-centred feedback.

All in all, this research confirms that ideally all four accessibility components as defined by Geurs and van Wee (2013) – transportation, land-use, temporal and individual – should be included when evaluating perceived accessibility in order to allow comprehensive analyses. In the future – once the perceived accessibility factors are adequately explored – researchers can contribute by developing appropriate measures for perceived pedestrian accessibility that enable planners and policymakers to eradicate the deficiencies in perceived pedestrian accessibility (to railway stations and other destinations). Therefore, the right balance between “rigor (soundness) and their practical relevance (plainness)” (Papa et al. 2015) needs to be found in order to meet the needs from planning practice.

6. Analysis of the quality of footpaths to schools: Development of indicators based on OpenData

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Abstract

Children in Germany are increasingly suffering from a lack of exercise, so walking to school should be encouraged. For people to walk, however, an attractive and safe walking environment is necessary. There are numerous approaches to assessing walkability. However, there is a lack of a transferable Walkability Index adapted to the German context. Based on a large number of open data sets, a multi-criteria approach of a Walkability Index was developed for the pilot municipality of Freiburg. This is integrated into the web-based planning tool Geo Open Accessibility Tool - GOAT and shows the quality for pedestrian traffic per path section. In order to be able to prioritise specific measures for improving walkability, an algorithm for calculating pedestrian potential flows was also developed. Starting from all residential buildings, this algorithm calculates the shortest route to selected destinations. The possible application of the developed indicators is explained in this article using school routes as examples.

6.1. Introduction

Children and adolescents in Germany do not exercise enough. Between 2014 and 2017, only 25% of children and adolescents met the WHO recommendation (Bull et al. 2020) of at least 60 minutes of physical activity per day (Robert Koch-Institut 2018). Due to the current pandemic, many children suffer even more from a lack of exercise (Schmidt et al. 2020). This poses a major challenge because exercise is very important, especially for young people. Regular exercise promotes cognitive, mental and physical development and supports learning and the ability to concentrate at school (Keller 2006; Wunsch et al. 2021).

Travelling to school on foot or by bicycle can be a partial solution to the lack of physical activity among children. Ideally, this is done together with other classmates, thus strengthening social interaction at the same time (Schweizer 2014). By walking or cycling everyday journeys, people's physical activity habits can also be formed at an early age, which can also have an impact on their physical development and mobility decisions in adulthood (Limbourg, Flade, and Schönharting 2000; Flade 1997). Since the most frequent cause of death among children between 10-14 years of age is bicycle accidents (Keller 2006), the promotion of walking in particular is seen as an effective means of promoting children's health. Pedestrian traffic is not only important for the development of children, but also an essential component of the mobility transition (Schneidewind and Fischedick 2016). Currently, 22% of all journeys in Germany are made on foot, and for children (0-9 years) even 32% (infas 2018). This is a significant share that should be further promoted through appropriate measures. Walking has numerous advantages over other modes of transport. Walking is easy, social, cost-effective, spatially efficient, climate and environmentally friendly and promotes the local economy (Jou 2011), prosperity (Florida 2014; Oishi, Koo, and Buttrick 2019) and the overall quality of life in a neighbourhood (Rogers et al. 2011). Taking all these benefits into account, walking can be considered the most sustainable of all transport modes (Jou 2011; Norzalwi and Ismail 2011).

In order to sustainably shape mobility behaviour at an early stage, it is therefore essential to promote walking among children by providing an attractive and safe walking infrastructure.

6.2. Walkability

Perceived pedestrian friendliness can be summarised under the term "walkability" and is defined as "the quality of walking conditions in an urban space which is inclusive of comfort, safety, connectedness and permeability (inclusiveness of neighbourhood design)" (Litman 2003). The walkability of a path depends on numerous factors, such as pavement width, land use, traffic impacts, safety and aesthetics (Cervero and Kockelman 1997; Frank and Pivo 1994; Lopez-Bernal 2013), which make its assessment a complex and challenging process.

There are numerous approaches worldwide that calculate a walkability index based on a selection of quality criteria. Perhaps the best known of these indices is the *Walk Score* ®, which is mainly used in the American context. It uses data on land use, existing destinations, population density and connectivity of the street network to calculate how pedestrian-friendly a neighbourhood is (Walk Score 2021). But there are also numerous other approaches, such as the *Pedestrian Environment Data Scan – PEDS* (Clifton, Livi, and Rodriguez 2007), the *Systematic Pedestrian and Cycling Environmental Scan – SPACES* (Pikora et al. 2002) or the *Neighbourhood Environment Walkability Scale – NEWS* (Saelens and Sallis 2002). Overall, the authors have found over 30 different approaches to assessing walkability through a literature and web search. These can be divided into objective and subjective approaches. In the objective[7] approaches, walkability is calculated based on spatial data, as in the *Walk Score* ®, for example. If the necessary data is available, these approaches can theoretically be transferred to application areas worldwide. Subjective approaches, such as *NEWS*, are based on surveys that were conducted for the respective study area. The disadvantage of these approaches is that the results are not transferable per se. On the other hand, the studies are usually more extensive and the results more representative. This is partly due to the fact that the existing objective approaches usually only take into account a small selection of the numerous influencing factors due to limited data availability and thus only achieve representative results to a limited extent. In addition, these approaches were primarily developed in the US (cf. *Walk Score ®, Pedestrian Potential Value, National Walkability Index, Pedestrian Environment Factor*), which differ greatly from the German structures.

Therefore, there is a need for new approaches adapted to the German context. Due to the fact that the quality and availability of open data sets has improved considerably in recent years, there are currently new possibilities to carry out much more detailed analyses than before. This has motivated the authors to use the available data to develop a multi-criteria, objective approach to quantifying walkability that is both representative and transferable.

6.3. Development of a walkability index

As part of a hackathon, the authors developed a first test prototype of a walkability index based on open data for a district in Munich. This index shows how attractive each route section is for walking. Technically, the index is embedded in the web-based accessibility tool GOAT (Geo Open Accessibility Tool). In this tool, the Walkability Index can be displayed as an additional layer and thus complement the already existing analysis options in GOAT (Pajares et al. 2021; Plan4Better GmbH 2021b; GOAT-Community 2021). In a subsequent innovation phase, the Walkability Index was transferred to the pilot municipality of Freiburg on a test basis, the underlying methodology was consolidated and the quality criteria considered were expanded.

6.3.1. Indicators and weighting

The Walkability Index developed includes 22 sub-indicators that can be grouped into six categories: Walking Comfort, Protection from Traffic, Lighting & Subjective Safety, Livability & Walking Environment, Vegetation & Waters and Urban Amenities (see *Table 14*). The weighting of the sub-indicators is based on various scientific studies (Blečić, Cecchini, and

[7] The term "objective" is used here to distinguish between the different approaches. However, it should be made clear that no completely objective approaches to walkability exist. Since a large part of the data is collected and interpreted by humans, subjective assessments are always included to a certain extent.

Trunfio 2015; D'Arcy 2013; Spittaels et al. 2009; Vale, Saraiva, and Pereira 2016; Kevin Manaugh and El-Geneidy 2011) and was adapted to local data availability.

Quality criteria for which the data availability in the accessible data sets was too low (e.g. path width) were not taken into account in the index. If no information was available for individual sub-indicators for individual paths, the other sub-indicators of the same indicator category were weighted correspondingly higher, so that the total weight of the indicator categories remained constant in each case.

Table 14: Indicators of the Walkability Index and their weighting

Walkability indicators	Sub-indicators	Weighting	
Walking comfort	Pavement availability	0.073	∑ 0.182
	Gradient	0.036	
	Surface	0.036	
	Path category	0.036	
Protection from road traffic	Number of lanes	0.027	∑ 0.273
	Speed limit	0.055	
	Number of road crossings	0.027	
	Parking spaces	0.064	
	Traffic accidents	0.027	
	Noise	0.073	
Lighting & Subjective safety	Street lamps	0.065	∑ 0.091
	Underpasses	0.026	
Liveliness & Walking Environment	Land use	0.061	∑ 0.182
	Points-of-Interest	0.061	
	Population	0.061	
Vegetation & Waters	Vegetation and waters	0.182	∑ 0.182
Urban equipment	Bench availability	0.021	∑ 0.091
	Bin availability	0.030	
	Public toilets	0.030	
	Fountains	0.009	

6.3.2. Data

The Walkability Index is based on crowdsourced data sets (Volunteered Geographic Information - VGI) such as OpenStreetMap, as well as data from OpenData platforms of public authorities, such as the FreiGIS of the city of Freiburg (see *Table 15*).

Table 15: Objects on which the index is based and their data sources

Objects	Data source
Path network with attributes	OpenStreetMap
Points-of-Interest	OpenStreetMap + FreiGIS
Land use	OpenStreetMap + ATKIS + UrbanAtlas
Buildings	OpenStreetMap + FreiGIS
Noise mapping	FreiGIS
Crossing possibilities	OpenStreetMap + Mapillary
Urban equipment	OpenStreetMap + Mapillary
Accident frequencies pedestrian traffic	Statistikportal
Population (Census)	Statistische Ämter des Bundes und der Länder
Vegetation (NDVI)	Sentinel-Hub
Slope (DGM)	DTM Germany 20m v1

The use of Mapillary data was particularly innovative. Mapillary is a platform for collecting and sharing georeferenced photos of road space (Mapillary 2021). Numerous objects (e.g. street lamps, traffic signs) can be recognised and read from these image sequences using automated AI algorithms.

In order to test this data source, more than 10,000 georeferenced images of the pilot municipality of Freiburg were captured with a GoPro action cam in Mapillary (the images are often already available in other cities). The original images (see *Figure 30 - Images*) are divided into classified segments by Mapillary's AI algorithms (*Object Detection*) and the georeferenced position is derived for the recognised objects by means of triangulation (*Map Features*). The recognised objects can be retrieved via an API. For the Walkability Index, information on street lamps, park benches and street crossings was obtained and merged with the OpenStreetMap data (see *Table 14*).

Figure 30: Processing steps of Mapillary's object recognition algorithms (Source: image captures from Mapillary (2021)).

6.3.3. Calculation

The spatial data were stored and processed in a PostgreSQL/PostGIS database. Information on all sub-indicators was stored for each route section. Based on a developed evaluation scheme, a value between 0 and 100 was assigned to each subindicator. The values were derived from numerous studies (cf. Blečić et al. (2015)) on the perceived influence of the respective element on walkability. According to the weighting in *Table 14*, these were added up to an overall score.

6.3.4. Result and application

Figure 31 shows the resulting Walkability Index for the pilot municipality of Freiburg. Through the integration into the web tool GOAT, the quality of the footpath network can thus be displayed in an interactive web map. For paths that are shown in dark green (e.g. pedestrian zone of Freiburg city centre), a high walkability was calculated. Orange paths (e.g. along the railway tracks and major roads), on the other hand, achieve a low walkability score and are thus classified as less pedestrian-friendly.

The Walkability Index can be used to identify weak points in the path network. In order to be able to set priorities in the improvement of the footpath infrastructure, information on the frequency of use of paths is also necessary.

Figure 31: Screenshot of the Walkability Index implemented in GOAT (Source: Plan4Better GmbH 2021a)

6.4. Development of pedestrian potential flows

For this purpose, a new indicator called “pedestrian potential flows” was developed. This can be used to show important route axes, e.g. to primary schools, and to focus them in the planning. Based on this application example, the calculation of pedestrian potential flows is explained below.

6.4.1. Calculation

Population data serve as the basis for the calculation. For the pilot municipality of Freiburg, the proportion of children between 6 and 9 years of age was known for each district. Thus, it was possible to calculate the average number of children living in each residential building. In the next step, the shortest route to the primary school of the respective primary school district was calculated from all residential buildings. By adding up the individual flows, the aggregated pedestrian potential flows are obtained.

6.4.2. Result and application

Figure 32 shows the calculated pedestrian potential flows to primary schools in Freiburg. The thickness of the turquoise lines indicates how many children potentially walk this route.

Figure 32: Screenshot of the pedestrian potential flows implemented in GOAT (Source: Plan4Better GmbH (2021))

Paths that are highly frequented but at the same time have a low walkability should be prioritised in the planning in order to create a comfortable and safe walking environment for the children and thus promote pedestrian traffic.

6.5. Conclusion

The assessment of walkability is a complex challenge that requires both a multicriteria approach and a large amount of data. The walkability index developed here was tested in a workshop with planners from the city of Freiburg and found to be useful. However, in order to represent the entirety of pedestrian friendliness, further data (e.g. on pavement width) is needed. A possible data source for this is the extraction of further information from the

Mapillary images. In this paper, the use of the walkability index in interaction with the pedestrian potential flows was explained using the example of school routes to primary schools in Freiburg, but the developed indicators could also be used for other route purposes and transferred to other study areas. Furthermore, the development of user-specific walkability indices, calibrated to the specific needs of the user group (e.g. children) depending on the destination under consideration, is seen as a potentially valuable further development.

7. How does pedestrian accessibility vary for different people? Development of a Perceived user-specific Accessibility measure for Walking (PAW)

Ulrike Jehle, María Teresa Baquero Larriva, Mahtab BaghaiePoor, Benjamin Büttner (2024): How does pedestrian accessibility vary for different people? Development of a Perceived user-specific Accessibility measure for Walking (PAW). Transportation Research Part A: Policy and Practice, 189, 104203. https://doi.org/10.1016/j.tra.2024.104203.

Abstract

Current accessibility measures assume that all people are the same, whereas in reality there are many different user groups with different needs and perceptions. Furthermore, the concepts of walking accessibility and walkability are often analysed independently from each other. This leads to a mismatch between calculated accessibility and perceived accessibility. This paper seeks to propose a new methodological approach that considers user-specific perceptions and walkability needs when calculating pedestrian accessibility. A Perceived user-specific Accessibility measure for Walking (PAW) is developed for four sample user groups: seniors, children, women, and wheelchair users. This is done by adjusting the Geo Open Accessibility Tool (GOAT) and imputing the perceptions. Per user group, the most important walkability attributes are therefore included in the accessibility formula and weighted according to their relevance based on the literature review using the Analytic Hierarchy Process (AHP) method. Results for a district of Munich, Germany are visualised. When juxtaposed with conventional time-based accessibility measures, our results unveil a more nuanced understanding of pedestrian infrastructure and its variabilities across different user demographics. This approach can help to provide a more realistic portrayal of pedestrian accessibility and to uncover critical gaps in current infrastructure, tailored to the needs of diverse population groups. The method can assist urban and transport planners in designing more inclusive, equitable urban environments. This contributes to a shift towards cities that are not only walkable but also attuned to the diverse needs and perceptions of their residents, ultimately enhancing quality of life and promoting equitable access to urban amenities.

7.1. Introduction

In order to create “cities for people” (Gehl 2010) that are walkable for all, it is crucial to consider the needs of the different users. To open up this perspective, we need new planning instruments that take the needs of different user groups into account. For walking, *accessibility* is one of the fundamental needs (see *Figure 33*), coming right after *feasibility*, which refers to the practicality or viability of a walking trip (Alfonzo 2005). In this context, *accessibility* refers to the “potential of opportunities for interaction” (Hansen 1959), which is dependent on the proximity of destinations and the connectivity of the paths (Handy 1996). Thus, accessibility instruments are suitable tools for evaluating and improving the walking conditions in a city.

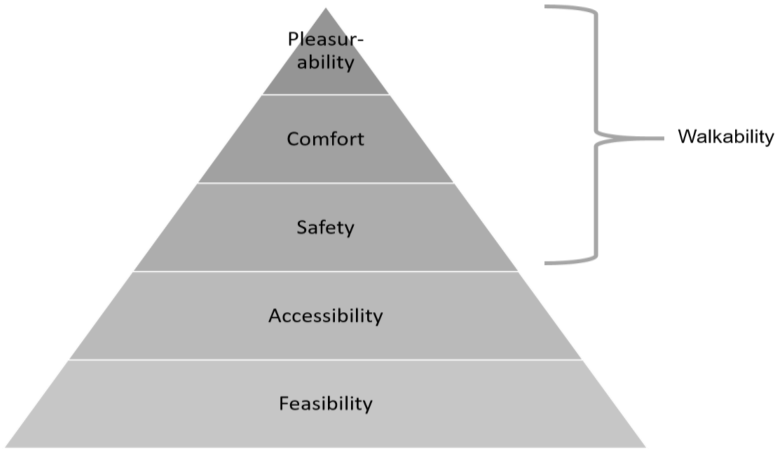


Figure 33: The concept of the hierarchy of walking needs (Adapted from Alfonzo (2005))

However, to fulfil the needs of pedestrians, it is not enough just to provide destinations and connected paths; the paths also need to be safe, comfortable and pleasant – in other words, *walkable*. Being w*alkable* means that “residents of all ages and abilities feel that it is safe, comfortable, convenient, efficient, and welcoming to walk, not only for recreation but also for utility and transportation” (American Planning Association 2006). Depending on the walkability of a place, the pedestrian perceives the walking time differently, i.e., attractive routes feel shorter than unattractive ones (Bahn.Ville 2-Konsortium 2010; Ralph et al. 2020; Gehl 1971). *Perception* is subjective and refers to how something is understood or interpreted. Exactly how a path is perceived depends strongly on a person’s characteristics, abilities and resulting needs. Thus, the perception differs among users.

7.1.1. Accessibility

After the first definition of accessibility by Hansen (1959), which focused on the proximity of destinations, the definition was expanded to include the *ease* with which the destinations can be reached (Koenig 1980; Niemeier 1997). In 2000, the definition was further expanded by Bhat et al. (2000) to “a measure of the ease of an individual to pursue an activity of a desired type, at a desired location, by a desired mode, and at a desired time”, now including the *ease* *of an individual*. Following this, Geurs and van Wee (2004) defined accessibility as "the extent to which land use and transport systems enable (groups of) individuals to reach activities or destinations by means of a (combination of) transport mode(s)" and cluster its influential factors into four components: land-use, transportation, temporal and individual. Hence, over time, individual(s) have gained a central role in the accessibility concept. However, at the same time, the individual component is often neglected in practice (Amaya et al. 2022) with most of the walking accessibility studies assuming that calculated travel distance and/or travel time are the only factors influencing walking accessibility (Merlin and Jehle 2023), disregarding other factors such as personal abilities and perception.

Accessibility studies can be divided into two approaches: *calculated* and *perceived* analyses. *Calculated* analyses calculate accessibility using spatial data, while *perceived* analyses are based on surveys or reported data. When comparing the results of both approaches for one specific study area, many studies found a mismatch between calculated accessibility and perceived accessibility (Curl, Nelson, and Anable 2015; Damurski, Pluta, and Zipser 2020; Finger and Jedrychowski 1989; Gebel et al. 2011; Jehle et al. 2022; Lättman, Olsson, and Friman 2018; McCormack et al. 2008; Pot, van Wee, and Tillema 2021; J. Ryan and Pereira 2021; M. Ryan et al. 2016; van der Vlugt, Curl, and Wittowsky 2019; Wilson et al. 2004). This leads to an overestimation of accessibility levels (Curl, Nelson, and Anable 2015; J. Ryan and Pereira 2021). The reason for this is the missing perception of different user groups in the calculated accessibility measures. The measures treat all people the same, although "the key is to measure accessibility in terms that matter to people in their assessment of the options available to them (Handy and Niemeier 1997). […] For the transportation component of accessibility, this means knowing something about what characteristics of different modes of travel matter to people" (Handy and Clifton 2000). For walking, it is therefore necessary to work with imputed perceptions (Merlin and Jehle 2023), i.e., to include the walkability elements and user group specific perceptions in order to achieve more realistic results.

7.1.2. Walkability

While *walking accessibility* is about the existence of destinations and connected pedestrian routes to get there, *walkability* is mainly about how easy it is to walk the routes and/or how surroundings are perceived by people. Many studies have proven that the walkability has an impact on walking behaviour (Carver et al. 2005; De Vries et al. 2010; Owen et al. 2004; Timperio et al. 2004; Wendel-Vos et al. 2004). Although there are many different definitions of *walkability*, most of them name "safety", "comfort" and "pleasurability" as key elements (American Planning Association 2006; Litman 2003; Spoon 2005). Each of those elements is influenced by a multitude of walkability attributes, such as sidewalk width, land use and presence of vegetation (see e.g. Jehle et al. 2022).

However, some walkability definitions also include the terms “accessibility”, “connectivity” and “presence of destinations” (Southworth 2005; Spoon 2005), which shows the strong links and sometimes fluid boundaries between the concept of accessibility and walkability. In summary, it can be said that the concepts of walkability and accessibility complement each other. Thus, in order to generate realistic analyses, the components from both concepts should be merged and considered in a more integrated way. Some studies, such as Jonietz and Timpf (2012), Anciaes, Nascimento, and Silva (2015), D’Orso and Migliore (2018), Erath et al. (2017) and Blečić, Cecchini, and Trunfio (2018) have already developed first approaches in which walkability attributes were integrated in walking accessibility measures. However, they assumed that walkability is the same for all pedestrian groups, which is not the case (Chan, Schwanen, and Banister 2021).

7.1.3. Integration of user needs

According to the capability approach, the capability of a person is related to two main elements: first to the intrinsic ability of the person (combination of all their physical and mental abilities) and second to the characteristics of the environment that affect that capability (Nussbaum 2003). In other words: people themselves are not disabled, but they are disabled by the environment; for example, stairs without a ramp disable wheelchair users.

The way a person perceives the walking environment depends on multiple personal, social, cultural and economic factors, such as age, gender, nationality and income, which differ among users; thus, each person has their own perception. This individual component is considered in the theoretical accessibility concept but is only applied in very few studies.

Focusing solely on walkability (without access to destinations), there are some user-specific walkability studies. For example, Moura, Cambra, and Gonçalves (2017) measure walkability for four different pedestrian groups: children, adults, seniors and impaired pedestrians. They find that: “differentiating the analysis for different types of pedestrian groups and/or trip motives does have a significant impact on the walkability evaluation. What is a reasonably good walking environment for fit adults can be a lot less convenient for seniors or even bad for impaired mobility pedestrians”. Beale et al. (2006) developed customisable routing for wheelchair users, which takes slope, surface and obstacles into account as impedances. Furthermore, the popular walkability survey NEWS (Neighbourhood Environment Walkability Scale) (Saelens et al. 2003) was adjusted to serve the needs of different user groups, such as the NEWS-Y for youth (Rosenberg et al. 2009) or the NEWS-CC for Chinese children (He et al. 2021).

Likewise, some user-group specific walking accessibility studies were found. For example, García-Palomares, Gutiérrez, and Cardozo (2013) use different walking distance thresholds and decay functions for different age groups. Cheng et al. (2019) investigate walking accessibility to recreational amenities for elderly people by using adaptive thresholds for walking distances. Both focus on the fact that accessibility changes as a consequence of differences in individual willingness to reach destinations (Arranz-López et al. 2019); however, they did not include walkability attributes.

Two recent studies were found that consider all three – accessibility, walkability and differentiation per user group. Amaya et al. (2022) assessed accessibility for three different user groups: older adults in good health, older adults with a chronic disease, and older adults with reduced mobility. To do so, they considered the pedestrian network, facilities and shops, public benches, slopes and gradients. They state that “the present findings provide a framework for accessibility analysis. Policymakers and urban planners should be aware that accessibility is sensitive as it is conditioned not only by the environmental and urban factors of the territory, but also influenced by the physical and health characteristics of the study population.” Gaglione, Cottrill, and Gargiulo (2021) measured accessibility of older people by taking ten walkability attributes into account (slope, sidewalk width, surface, illuminance, traffic volume, presence of escalators, presence of benches, presence of green areas, presence of panoramic points, road type). However, both studies point out the limitation that only selected walkability attributes were considered and see a need for further research that includes additional walkability attributes.

7.1.4. Research gap and objective of the paper

Summarising the current findings, we follow the hypothesis that one accessibility index alone is not sufficient to represent all individual needs, capabilities and preferences. Rather, a variety of user-specific indices is required. Thus, urban and transport planners currently lack appropriate measures for analysing how different people perceive walking accessibility to different destinations. Consequently, it is crucial to include accessibility as well as walkability attributes because both influence the perceived walking accessibility. The goal of this paper is to develop a methodological approach of an “**P**erceived user-specific **A**ccessibility measure for **W**alking (**PAW**)”, following the recommended practice of Merlin and Jehle (2023). This can be achieved by using perceived travel time as impedance and including the users perceptions on path and environmental attractiveness (Boakye-Dankwa et al. 2019; Gaglione, Cottrill, and Gargiulo 2021).

One key activity thereby is to identify the most relevant attributes for measuring walking accessibility for different user groups based on age, gender and capabilities. As walking needs and perceptions not only differ based on people, but also based on places (Jehle et al. 2022), a global review on perception studies provides an average across different cities and countries.

While Chan, Schwanen, and Banister (2021) see the application of different weights as appropriate when large enough sample sets are taken into account, the primary goal of this research is not to conclusively evaluate the impact of each individual attribute, but rather to establish a versatile method that can be adapted according to varying input parameters and applied in diverse contexts.

7.2. Methodology

Aiming to close this research gap and to take user-specific perceptions and needs into account when analysing walking accessibility, PAW was developed for four sample user groups based on gender, age and capabilities: children, seniors, women and wheelchair users. [8] The methodology has been divided into several stages, which will be explained in detail in the following sections. *Figure 34* provides an overview.

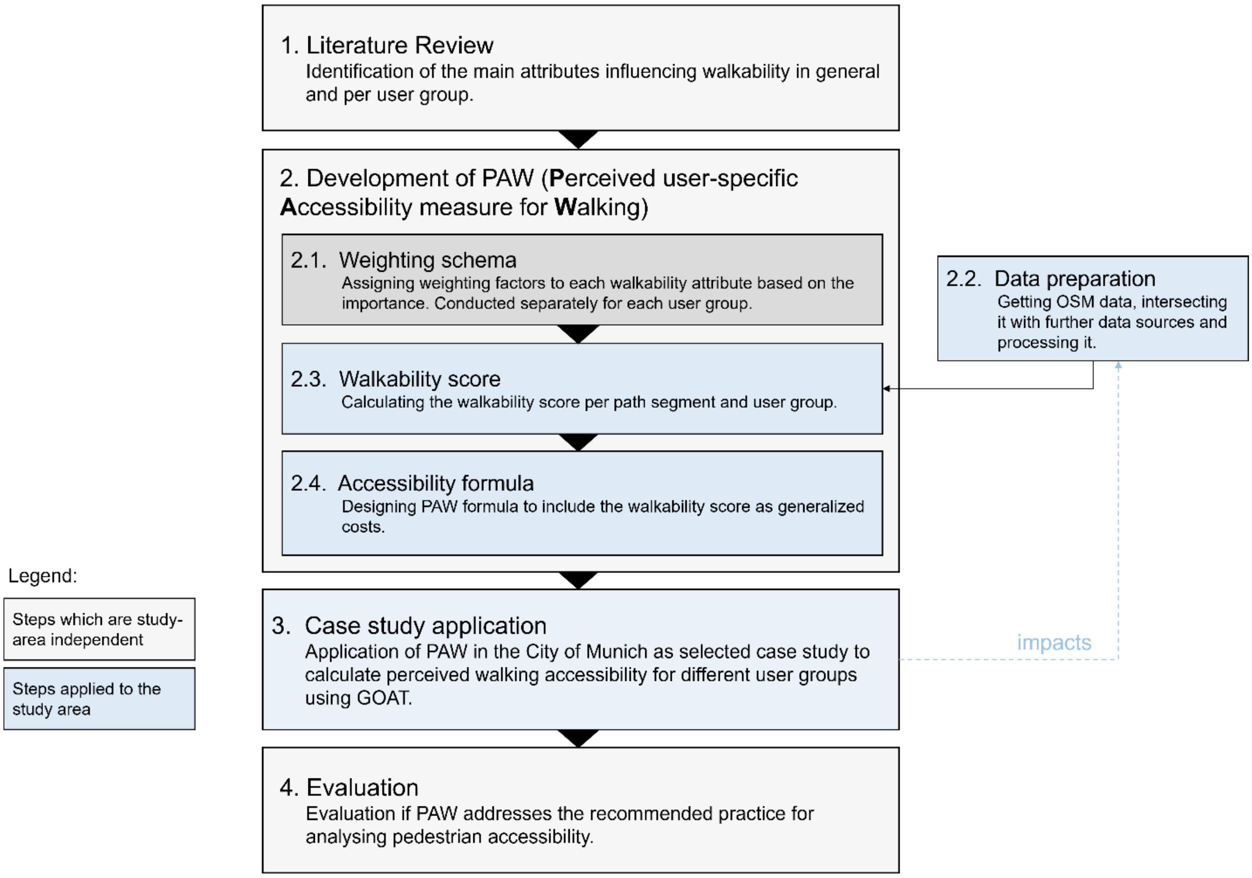


Figure 34: Methodological overview

7.2.1. Literature review

First, a literature review was conducted, focused on walkability studies to identify the main attributes that influence walkability in general (see *Section 7.3.1*) and then specified to

[8] Although we use these user groups as representative groups to identify with, we acknowledge that each of these groups includes heterogeneities in terms of perception and needs that cannot be generalised as they depend on various personal, social, cultural or economic factors.

walkability for each of the four selected user groups (see *Section 7.3.2)*. The main keywords for the selection criteria were among others "walkability", "walking", "walkability perception", "pedestrian", "pedestrian planning", "urban design", "built environment", "pedestrian comfort", "walkability score", "walking accessibility" and "street design", together with "seniors", "women", "children" and "wheelchair users" respectively for the user group. To determine the needs and preferences per user group, only articles or guidelines that provided some kind of analysis or ranking of the walkability attributes were selected. A total of 121 articles were reviewed and 40 were selected as input for the weighting schema, based on the included user group perception and evaluation data.

7.2.2. PAW development for each user group

After identifying the most important walkability attributes from the literature review, the development of PAW was performed in four stages.

7.2.2.1. Weighting schema

For each of the identified walkability *attributes* ***a***, its perceived impact for each *user group* ***u*** was analysed and translated into a numerical *weighting factor* $z_{u,a}$ by first conducting a pre-analysis and then using the Analytic Hierarchy Process Online System (AHP-OS)[9]. This system was developed by Goepel (2018) based on the AHP methodology developed by Saaty (1987); which has also been used by other studies in this field (e.g. by Arranz-López et al. 2017; Gaglione, Cottrill, and Gargiulo 2021). AHP is a method to support multi-criteria decision making that derives ratio scales from paired comparisons of criteria. Inputs can be actual measurements, but also subjective opinions (Goepel 2018). As a result, weightings and consistency ratios are calculated. Mathematically the method is based on the solution of an eigen value problem (for further explanation see Taherdoost (2017); Goepel (2018)).

We chose this method because it allows the comparison and ranking of different perceptual attributes in a rather objective way. It provides a systematic framework for bringing together the results of multiple studies and reaching a consensus based on the combined input. *Figure 35* summarizes the steps of the weighting schema. These are performed for each user group separately. To ensure consistency in the rating, this whole weighting process was conducted by two of the authors whereby each of them was responsible for one or more user groups. For each user group, 10 research papers were considered that assessed their perception of walkability.

[9] Available at: https://github.com/bpmsg/ahp-os

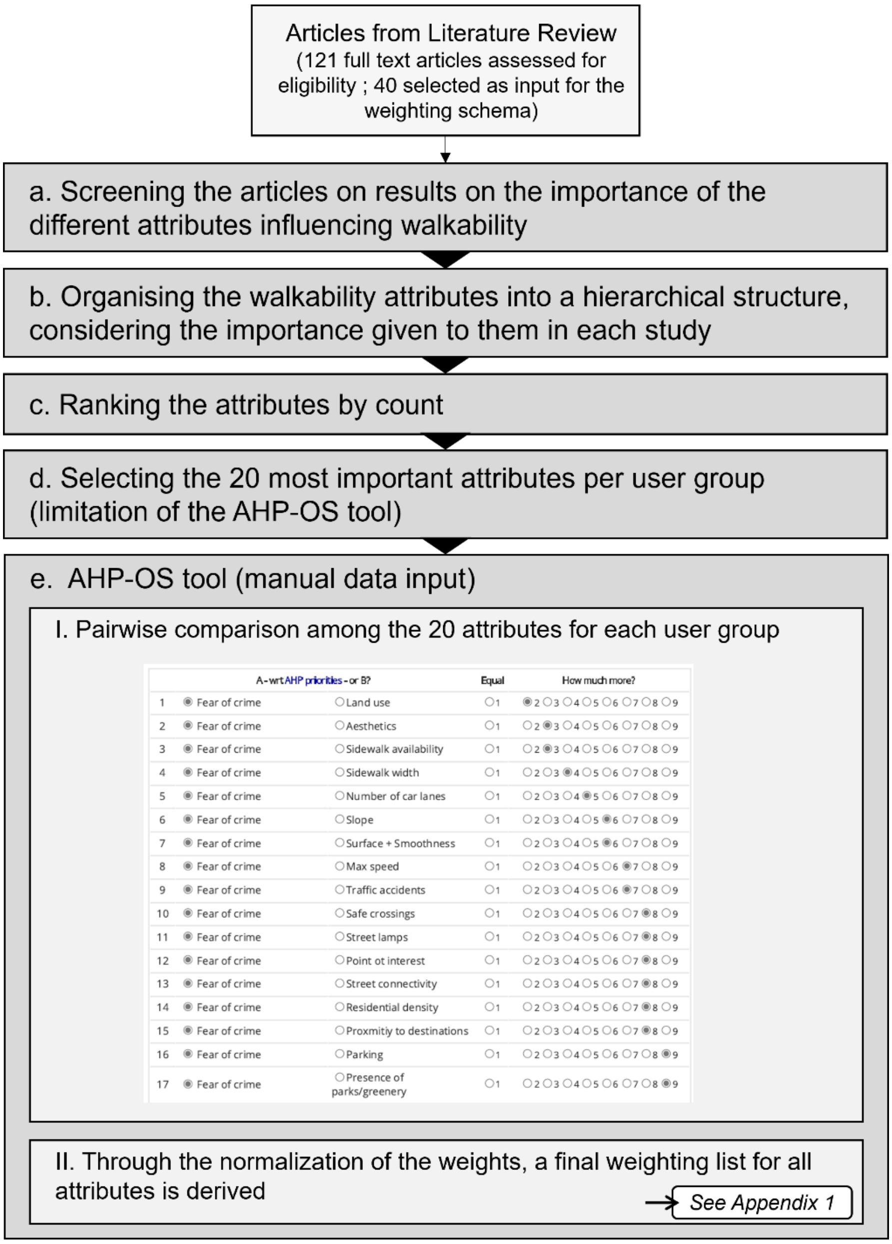


Figure 35: Method to derive the weighted attributes per user group

In detail, the following steps are performed, separately for each user group:

a. We searched for studies that address the importance of different walking attributes (see *Figure 35-a*).

b. The walkability attributes were organised into a hierarchical structure in an Excel spreadsheet, considering the importance given to them in each study (see *Figure 35-b*). For this purpose, we gave them an initial value according to their importance (1 = most important; 2 = second most important; etc.) in each study. While some papers provided a clear ranking of the attributes, others only roughly described the importance in the text. Thus, sometimes the ranking had to be done subjectively by interpreting the provided text.

c. We ranked the attributes based on the number of these values. For example, the attribute with the highest number of "1 (most important)" values was rated as the most important attribute across all studies. The result was a final list with a ranking of walkability attributes (see *Figure 35-c*). If two different attributes resulted to have the same importance, they are sharing a ranking position.

d. Based on this result, we selected the 20 most important attributes (as AHP-OS is limited to this number of input variables) and established the priority order (see *Figure 35-d*).

e. We manually input the data into the web tool AHP-OS to perform the pairwise comparisons between all attributes (190 pairwise comparisons) to determine the relative importance of the attributes (see *Figure 35-e*). For this, each attribute is compared with the others to determine the relative importance, using a scale of 1-9, where 1 means equal importance, 3 means moderately more important, 5 means strongly more important, and so on. Same as for step b., the relative importance value is given by the authors according to the results of the reviewed articles. In some of the reviewed papers the relative importance was clearly stated, while in others it was rather subjective of how we interpreted the texts written by the researchers. The result is a pairwise comparative matrix. The software normalizes the weights and produces a final weighting list for all attributes.

The results of the weighting schema for all user groups can be found in *Subsection 7.3.2.5*. An extended version of the table with information on the references used is provided in *Appendix 1*.

To validate the results of the AHP, the APH-OS provides the *consistency ratio* ***CR***, which is calculated through following formula (Goepel 2018):

$$\boldsymbol{CR} = \frac{\boldsymbol{\lambda - n}}{\boldsymbol{2.7699 * n - 4.3513 - n}} \tag{4}$$

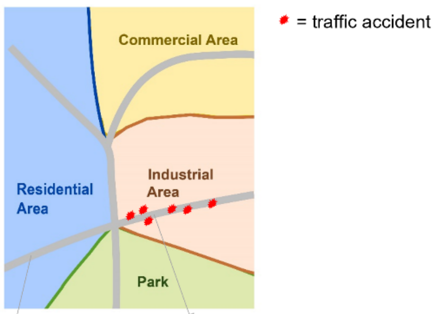
CR: Consistency ratio
λ: dominant eigen value of the pair wise comparison matrix
n: number of attributes

A CR of ≤10% is considered as acceptable to work with the results of the AHP analysis (Saaty 1987). This was fulfilled for all user groups (the achieved CR values per user group can be found in *Subsections 7.3.2.1* to *7.3.2.4)*.

7.2.2.2. Data preparation

For the development of the accessibility measure, the Geo Open Accessibility Tool – GOAT[10] developed by Pajares et al. (2021) was used as a basis and adjusted accordingly. The tool uses OpenStreetMap (OSM) data for the pedestrian network, which is found to be the richest data source for the walkability items, and can be fed with unlimited additional data sets.

To prepare the data for the study area, first, the walking network and the surrounding objects were derived from OSM and stored in a PostgreSQL / PostGIS database. From OSM, the path elements are already provided with information on some walkability attributes (e.g. street category, sidewalk availability, surface, smoothness, slope, wheelchair-usability, number of car lanes, maximum speed, parking, illuminance). Other walkability attributes refer to punctual objects (e.g. accidents) or polygon objects (e.g. land use). Using spatial queries, buffers around points were created and the polygons intersected with the paths. In this way, the information for all walkability attributes was derived and assigned to each respective path segment (see *Figure 36*).



Attribute a	Attribute value
Way category	Living street
Sidewalk availability	Both
Surface	Paving stones
Number of car lanes	0
Maxspeed	7
Illuminance	Yes
Land use	Residential
Traffic accidents	0
…	…

Attribute a	Attribute value
Way category	Secondary
Sidewalk availability	Right
Surface	Asphalt
Number of car lanes	4
Maxspeed	50
Illuminance	Yes
Land use	Industrial
Traffic accidents	6
…	…

Figure 36: Schematic illustration of the data preparation procedure

7.2.2.3. Walkability score

The methodology from the Walkability Index (WALKIE) developed by Jehle and Pajares (2021) is used to obtain one quantitative walkability score per *user group **u*** and *path segment **p***.

[10] Available at: https://github.com/goat-community/goat

First, all the *attribute values* are translated into *attribute scores* $\boldsymbol{s_a}$ (see *Figure 37-a*). To do so, a score range from 0 to 100 is used, with 0 indicating the lowest and 100 the highest quality. A medium value of 50 represents the ‘average’ walking quality. For example, an excellent smoothness is awarded 100 points, while an intermediate smoothness is awarded 50 points and an impassable smoothness 0 points. A table with all of the attribute scores is provided in the *Appendix 2*. Due to a lack of available studies on how each individual attribute value influences the walkability perception of a specific user group, the same value scores are used for all user groups. In this case, the attribute scores were defined specifically for this study area (based on the values that are found there).

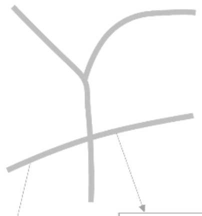
Second, the *attributes* $\boldsymbol{a}$ are matched with the respective *weighting factors* $\boldsymbol{z_{a,u}}$ for each *user group* $\boldsymbol{u}$ (see *Figure 37-b*). Third, a *walkability score* $\boldsymbol{w_{p,u}}$ is calculated per *path segment* $\boldsymbol{p}$ and *user group* $\boldsymbol{u}$ (see *Figure 37-c*), by the following formula:

$$\boxed{\boldsymbol{w_{p,u} = \sum_{a} s_a * z_{a,u}}} \qquad (5)$$

$w_{p,u}$: Walkability score of *path segment p* for *user group u*
s_a: Score of *attribute a*
$z_{a,u}$: Weighting factor of *attribute a* for *user group u*

As for the attribute scores, the walkability score ranges from 0 to 100, representing the ease of walking. The results are visualised in *Section 7.3.3*.

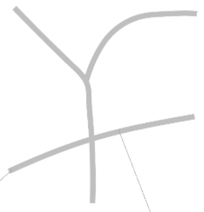
a. Translating *attribute values* into *attribute scores* s_a



Attribute a	Attribute value	Attribute score s_a
Way category	Living street	100
Sidewalk availability	Both	100
Surface	Paving stones	100
Number of car lanes	0	100
Maxspeed	7	100
Illuminance	Yes	100
Land use	Residential	100
Traffic accidents	0	100
…	…	…

Attribute a	Attribute value	Attribute score s_a
Way category	Secondary	20
Sidewalk availability	Right	80
Surface	Asphalt	100
Number of car lanes	4	0
Maxspeed	50	50
Illuminance	Yes	100
Land use	Industrial	0
Traffic accidents	6	0
…	…	…

b. Matching attributes with the respective *weighting factors* $z_{a,u}$ per *user group* u



Attribute a	Attribute value	Attribute score s_a
Way category	Living street	100
Sidewalk availability	Both	100
Surface	Paving stones	100
Number of car lanes	0	100
Maxspeed	7	100
Illuminance	Yes	100
Land use	Residential	100
Traffic accidents	0	100
…	…	…

x

Weighting factor $z_{a,u}$	
u = child	u = senior
0.027	0.061
0.164	0.211
0.015	0.025
0.032	0.081
0.032	0.081
0.033	0.009
0.132	0.020
0.177	0.000
…	…

Attribute a	Attribute value	Attribute score s_a
Way category	Secondary	20
Sidewalk availability	Right	80
Surface	Asphalt	100
Number of car lanes	4	0
Maxspeed	50	50
Illuminance	Yes	100
Land use	Industrial	0
Traffic accidents	6	0
…	…	…

x

Weighting factor $z_{a,u}$	
u = child	u = senior
0.027	0.061
0.164	0.211
0.015	0.025
0.032	0.081
0.032	0.081
0.033	0.009
0.132	0.020
0.177	0.000
…	…

c. Calculating the *walkability score* $w_{p,u}$ per *path segment* p and *user group* u

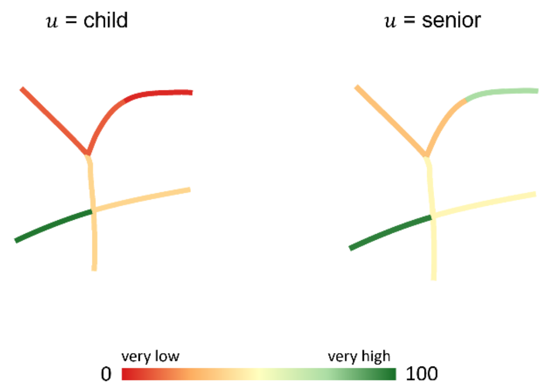


Figure 37: Schematic illustration of the walkability score calculation

7.2.2.4. Accessibility formula

To incorporate the walkability score of a specific user group in accessibility analyses, a contour-based accessibility measure (isochrone) was used as an approach, with limiting accessibility to walking and extending the generalised cost term by the walkability perceptions. Accessibility can be conceptualised using the following mathematical expression (Geurs and van Wee 2004):

$$\boldsymbol{A_i = \sum_j D_j f(c_{ij})} \qquad (6)$$

A_i: Accessibility of place i

D_j: Destination potential found at location j

c_{ij}: Generalised costs of travelling (**walking**) between i and j

$f(c_{ij})$: The impedance function applied to the generalised costs of travel between i and j

Contour-based measures show the number of opportunities that can be reached from one point within a certain distance, time interval or costs. They are valued for their easily interpretable results (Geurs and van Eck 2001; Albacete 2016), but have the drawback of not distinguishing between different travel times within the cut-off range $\boldsymbol{c_{max}}$ (Bertolini, le Clercq, and Kapoen 2005), as they follow basic impedance functions, such as (El-Geneidy and Levinson 2006):

$$\boldsymbol{f(c_{ij}) = \begin{cases} 1 & for\ c_{ij} \leq c_{max} \\ 0 & else \end{cases}} \qquad (7)$$

So far, the generalised cost term for walking is usually solely comprised of the time and uses an average speed for all users:

$$\boldsymbol{c_{ij}} = \frac{L}{v_\emptyset} \qquad (8)$$

L: Length [m]

$v_\emptyset$: Average speed [m/s]

For PAW, the formula has been extended by integrating walkability impedances and incorporating different speeds for different user groups:

$$\boxed{c_{ij} = \sum_p \frac{L_p * \left(\frac{50}{w_{p,u}}\right)}{v_{\emptyset u}}} \qquad (9)$$

L_p: Length of *path segment p* [m]

$v_{\emptyset u}$: Average speed of *user group u* [m/s]

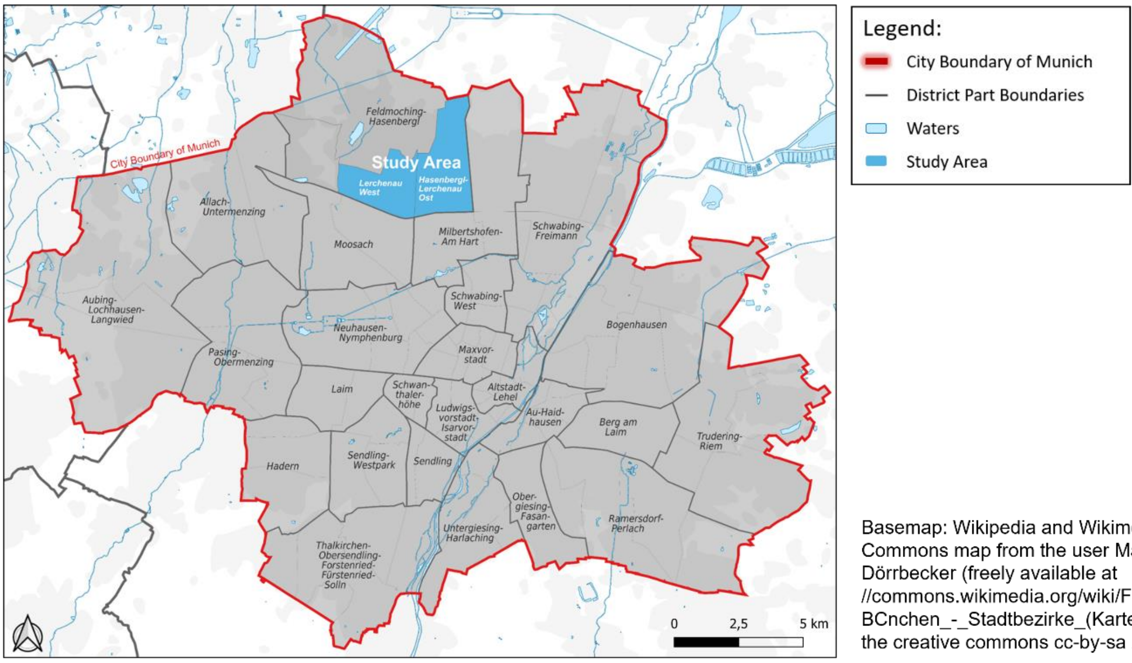
This imputes the perceptions and represents that a path sequence is perceived as longer if it is unattractive, and conversely that an attractive path segment feels shorter. Untermann (1984) claims that the acceptable walking distance can be doubled through high walkability levels. To represent this, the concept of “perceived time”, which has also been used by other authors in comparable studies (e.g. Erath et al. 2017; Gaglione, Cottrill, and Gargiulo 2021; Boakye-Dankwa et al. 2019), was applied. Therefore, for this study, the ‘standard’ walkability score is defined as 50. For walkability scores >50, the time is perceived shorter and for walkability scores <50, the time is perceived longer.

7.2.3. Case study application

To test the developed PAW, it was applied to a selected study area in the City of Munich.

7.2.3.1. Study area

Due to high level of OSM data completeness from a previous study (Jehle 2020), the Munich districts “Hasenbergl-Lerchenau Ost” and “Lerchenau West” were chosen as the study area (see *Figure 38*). The area has a diverse structure, including small single-family homes and large social housing blocks, as well as car-oriented commercial zones and pedestrian-oriented recreation areas. The study area covers an area of 869 ha and has 47,052 inhabitants (Landeshauptstadt München 2021).



Basemap: Wikipedia and Wikimedia Commons map from the user Maximilian Dörrbecker (freely available at //commons.wikimedia.org/wiki/File:M%C3%BCnchen_-_Stadtbezirke_(Karte).png under the creative commons cc-by-sa 2.5 license).

Figure 38: Study area

7.2.3.2. Analysis

PAW is calculated for the four selected user groups and compared with each other. Therefore, isochrones from three sample locations (childcare, supermarket, park) were calculated and intersected with population data from Census (Statistische Ämter des Bundes und der Länder 2011) as destination potential D_j. The catchment area c_{max} was set to 5 minutes of perceived time. The results are visualised in maps and are presented in *Section 7.3.4*. To allow a comparison with 'standard' time-based analyses, each map also contains a reference isochrone.

7.2.4. Evaluation

The recommended practice for analysing pedestrian accessibility developed by Merlin and Jehle (2023) was used as an overall framework to compare the proposed methodology with accessibility practice recommendations. The results are presented in *Section 7.3.5*.

7.3. Results

7.3.1. Main attributes influencing walkability

The main attributes that influence walkability were identified by the literature review and have been grouped into five categories: 1) Infrastructure quality and comfort; 2) Traffic safety and road influences 3) Security; 4) Environment and liveliness; 5) Urban equipment. As some attributes may have an effect on several categories, they were allocated to the category where the effect is considered to be higher. *Table 16* presents the list of these categories, their main attributes and the references from the literature review. In addition, the column "Data source" lists which data sources were available per attribute for the study area.

Table 16: List of walkability attributes from literature review and data availability for the study area

Walkability Categories	Attributes	References	Data source
Infrastructural quality and comfort	Way category	(Moura, Cambra, and Gonçalves 2017)	OSM
	Sidewalk availability	(Handy and Clifton 2001; McGinn et al. 2007; Lo 2009)	OSM
	Sidewalk width	(Alfonzo 2005; Southworth 2005; Arslan et al. 2018; Moura, Cambra, and Gonçalves 2017)	OSM
	Slope	(Handy and Clifton 2001; Wimbardana, Tarigan, and Sagala 2018; Clifton, Livi, and Rodriguez 2007)	DTM Germany 20m v1
	Surface + smoothness	(Alfonzo 2005; Wimbardana, Tarigan, and Sagala 2018; Moura, Cambra, and Gonçalves 2017)	OSM
	Segregation from bicycles	(Bundesamt für Strassen (ASTRA) and Fussverkehr Schweiz 2019)	OSM
	Signage, orientation	(Hillier et al. 2007; Gorrini and Bandini 2019; Ralph et al. 2020)	*n.a.*
	Freedom from barriers	(Lo 2009; Zakaria and Ujang 2015; Arslan et al. 2018)	OSM
	Shelter, shade	(Whyte 1980; Alfonzo 2005; Pilipenko, Skobeleva, and Bulgakov 2018; Erath et al. 2015; Hoogendoorn and Bovy 2004)	*n.a.*
Traffic safety and road influences	Spatial separation of footpath from road	(Saelens et al. 2003; Hillnhütter 2016)	OSM
	Number of car lanes	(Ewing 1999; Southworth 2005; Speck 2013)	OSM
	Traffic load	(McGinn et al. 2007; Hillnhütter 2016; Moura, Cambra, and Gonçalves 2017; Ortega et al. 2021)	*n.a.*
	Proportion of heavy goods vehicles	(Saelens et al. 2003; Arslan et al. 2018)	*n.a.*
	Noise	(C. E. Kelly et al. 2011; Erath et al. 2015; Hoogendoorn and Bovy 2004)	*n.a.*
	Emissions / air quality	(Fussverkehr Schweiz 2021; Hoogendoorn and Bovy 2004)	*n.a.*
	Max speed	(Saelens et al. 2003; Alfonzo 2005; Southworth 2005; McGinn et al. 2007)	OSM
	Safe street crossings	(Handy and Clifton 2001; Lo 2009; C. E. Kelly et al. 2011; Wimbardana, Tarigan, and Sagala 2018; Hoogendoorn and Bovy 2004; Moura, Cambra, and Gonçalves 2017)	OSM
	Traffic accidents	(Moura, Cambra, and Gonçalves 2017)	Statistikportal
	Parking	(Saelens et al. 2003; Clifton, Livi, and Rodriguez 2007; Erath et al. 2015)	OSM
Security	Illuminance	(Saelens et al. 2003; Wimbardana, Tarigan, and	OSM

Walkability Categories	Attributes	References	Data source
		Sagala 2018; Clifton, Livi, and Rodriguez 2007)	
	“Social hotspots” - fear of crime	(Saelens et al. 2003)	*n.a.*
	Underpasses	(Hillnhütter 2016; Jehle et al. 2022)	OSM
Environment and liveliness	Population density	(Crane 1996; Saelens et al. 2003; Marquet, Bedoya, and Miralles-Guasch 2017; Arslan et al. 2018)	Census
	Cleanliness	(Saelens et al. 2003; C. E. Kelly et al. 2011; Moura, Cambra, and Gonçalves 2017)	*n.a.*
	Vegetation and Water	(Clifton, Livi, and Rodriguez 2007; Speck 2013; Lin, Sun, and Li 2015; Rafiemanzelat, Emadi, and Kamali 2017; Wimbardana, Tarigan, and Sagala 2018; Hillnhütter 2021)	OSM
	Microclimate / inner-city aeration	(Pilipenko, Skobeleva, and Bulgakov 2018)	*n.a.*
	Land use	(Pushkarev and Zupan 1971; Southworth 2005; Wimbardana, Tarigan, and Sagala 2018; Gao et al. 2022)	OSM, ATKIS
	Number of Points-of-Interest (POIs)	(Saelens et al. 2003; Lin, Sun, and Li 2015; Hillnhütter 2016; Ortega et al. 2021)	OSM
	Aesthetics	(Lo 2009; Speck 2013; Lin, Sun, and Li 2015; Cervero and Kockelman 1997; Hillnhütter 2021)	*n.a.*
	Pedestrian flow rate	(Lo 2009; J. Jacobs 1961; Hillnhütter 2021)	*n.a.*
Urban equipment	Benches	(Alfonzo 2005; Hillnhütter 2016; 2021)	OSM
	Bins	(Alfonzo 2005; Hillnhütter 2016; Arslan et al. 2018)	OSM
	Public toilets	(Arslan et al. 2018)	OSM
	Water fountains	(Whyte 1980; Alfonzo 2005)	OSM

n.a. = no data available

7.3.2. Needs and preferences per user group

Pedestrian perception, preference and behaviour assessment can be complex because of the heterogeneities depending on various personal, social, cultural, economic, and geographical factors (Marquet, Bedoya, and Miralles-Guasch 2017; Halden, Jones, and Wixey 2005; Jaramillo, Lizárraga, and Grindlay 2012). For instance, a young strong person in a manual wheelchair might not perceive the walkability to be the same as another user with different strength or physical functionality, such as an older adult wheelchair user (Tseng 2020), or it may be that pedestrians in rural areas behave differently to urban pedestrians (Holzer 2018).

Despite the impossibility of calculating perceived accessibility precisely and accurately for each person, the estimates of a general sample calculation can provide valuable insights (Holzer 2018). Thus, based on a literature review on walking accessibility perceptions, four sample users as examples of diversity in age, gender, and mobility needs were selected: children, seniors, women, and wheelchair users.

The following *Subsections 7.3.2.1* to *7.3.2.4* provide a summary of the physiological and physical characteristics, behaviour and preferences found in the literature review for each of these user groups. In *Subsection 7.3.2.5*, the quantitative weighting factors are summarised.

7.3.2.1. Children

Children under 11 years old present specific physical characteristics such as small height, reduced field of vision, as well as motor and cognitive skills that are undergoing a natural developing stage (Grob and Michel 2011). This can affect their ability of movement and may make it difficult to notice them in street traffic. Their walking speed changes throughout the years from 1.29 m/s at 5 years old (Pinheiro, Hokugo, and Nishino 2014), to almost adult speed at 11 years old (Cavagna, Franzetti, and Fuchimoto 1983). Additionally, they are restless, easily distracted, and curious, they are learning to handle their emotions and have limited awareness of hazards (Grob and Michel 2011). These physical and mental characteristics lead to unpredictable behaviour. *Figure 39* shows the key walkability attributes for children that resulted from the AHP method. Safe infrastructure and protection from road traffic is especially important. Specifically, this means the availability of sidewalks (Rosenberg et al. 2009; De Vries et al. 2010; Davison and Lawson 2006; Zhao et al. 2021) and safe crossings (Hume, Ball, and Salmon 2006; De Vries et al. 2010; Molina-García et al. 2020; Davison and Lawson 2006; Zhao et al. 2021). A high number of roads that have to be crossed and high traffic density/speed are negatively associated with children's walking activity (Davison and Lawson 2006; Zhao et al. 2021). Parks are especially attractive to walk through (Timperio et al. 2004; De Vries et al. 2010; Rosenberg et al. 2009). Concerning the built environment, quiet neighbourhoods are found to have a positive impact (Hume, Ball, and Salmon 2006), while graffiti (Hume, Ball, and Salmon 2006) and crime (Davison and Lawson 2006) are found to have a negative impact on children walking.

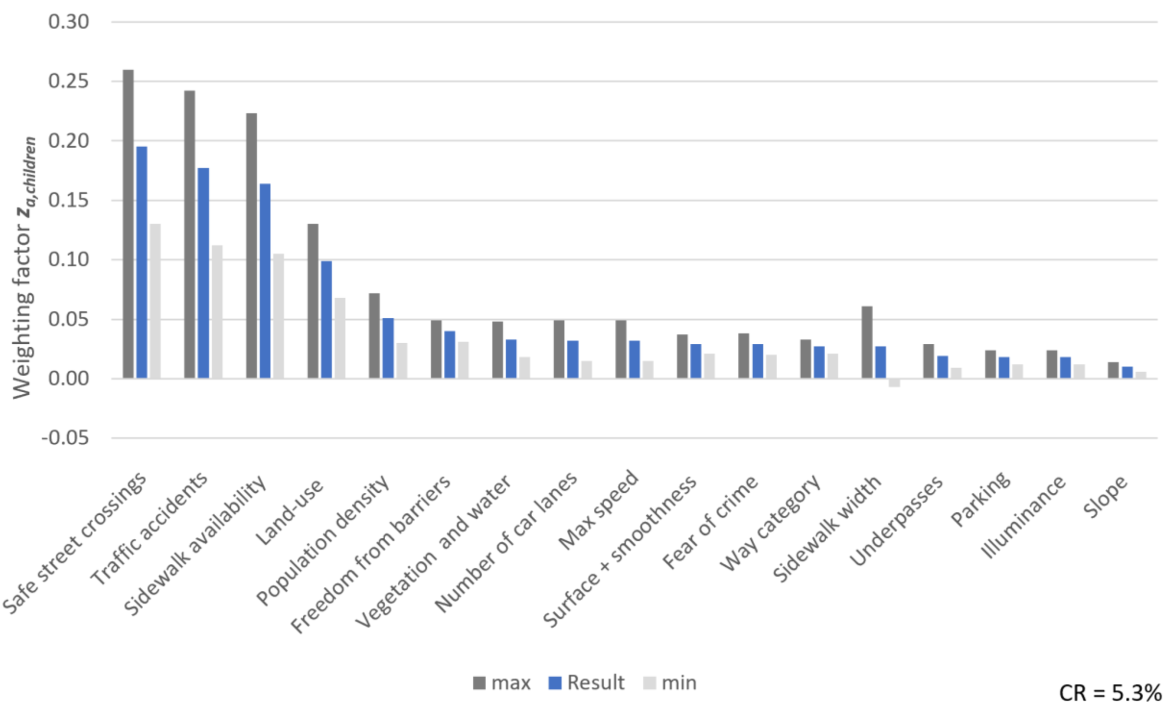


Figure 39: Key walkability attributes for children and their weights

7.3.2.2. Seniors

Ageing leads to a gradual decline in physical, sensory, and mental abilities, such as vision and hearing impairment (WHO 2015; Grob and Michel 2011; Loh and Ogle 2004). Seniors (here defined as humans >60 years old) are a heterogeneous group because health is related to different factors such as genetic predisposition, environment, and lifestyle. Nevertheless, the probability of chronic diseases rises with increasing age and the medication provided for, and symptoms of these can affect the independence, mobility, reaction time, and environmental perception of seniors (WHO 2015; Grob and Michel 2011). These physiological changes also affect walking speed. Although the speed of older people depends on their physical and mental health, it can be assumed that an average 70-year-old person walks at approximately 0.97 m/s (Grob and Michel 2011; Himann et al. 1988; Shkuratova, Morris, and Huxham 2004). With the loss of muscle strength and motor limitations (Grob and Michel 2011), the risk of falling increases. Falls are one of the greatest causes of morbidity among older people and are a determinant of mobility restriction (Gill et al. 2001). To prevent this, safe, comfortable and barrier-free footpaths are especially important. This includes the availability of sidewalks of sufficient width (Grob and Michel 2011) with smooth surfaces (Moura, Cambra, and Gonçalves 2017) and safe street crossings (Leonardi, Distefano, and Pulvirenti 2020; Distefano, Pulvirenti, and Leonardi 2021; Aronson and Oman 2004; Lockett 2005). With increasing age, slope becomes a bigger barrier (Moura, Cambra, and Gonçalves 2017) and walking becomes more and more tedious (Jehle et al. 2022), therefore, the availability of benches is crucial so people can rest. In *Figure 40*, the key walkability attributes for seniors that resulted from the AHP method are shown.

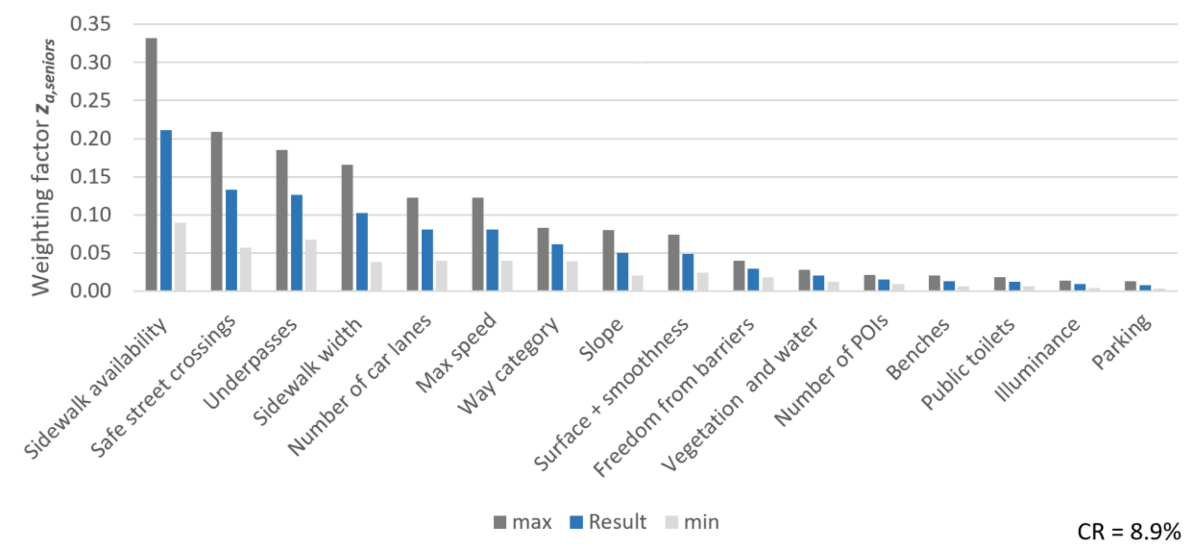


Figure 40: Key walkability attributes for seniors and their weights

7.3.2.3. Women

Several studies have found gender differences in walking behaviour (Adlakha and Parra 2020; Clifton and Livi 2005; Golan et al. 2019; Hatamzadeh, Habibian, and Khodaii 2020; Hille 1999; Nichani et al. 2019; Pelclová, Frömel, and Cuberek 2013; Rišová and Sládeková Madajová 2020). In general, women walk a bit slower than men (Coffin and Morrall 1995; Grob and Michel 2011; Montufar et al. 2007; Toor et al. 2001). The average walking speed of a woman between 30 and 40 years old is about 1.4 m/s (Bohannon 1997). One main psychological difference between men and women is the perception and experience of fear (Hille 1999; Loukaitou-Sideris 2014; Rišová and Sládeková Madajová 2020). The strong perception of fear leads to high security and safety needs. *Figure 41* shows the key walkability attributes for women that resulted from the AHP method. The biggest barrier to walking is the fear of crime (Golan et al. 2019), followed by land use (Hatamzadeh and Hosseinzadeh 2020) and the aesthetics of the environment. Fear experienced by many women leads to behavioural adjustments and precautions, such as not walking alone, avoiding certain locations, not travelling after sunset, not wearing certain types of clothing or jewellery (Loukaitou-Sideris 2014; Hille 1999), and may also lead to reduced activity in general (Adlakha and Parra 2020). Women are more aware of and more strongly influenced by their environment than men (Clifton and Livi 2005; Erath et al. 2015; Jehle et al. 2022). However, inconsistent results from different studies suggest that gender differences may vary across different geographical and cultural contexts (Pelclová, Frömel, and Cuberek 2013).

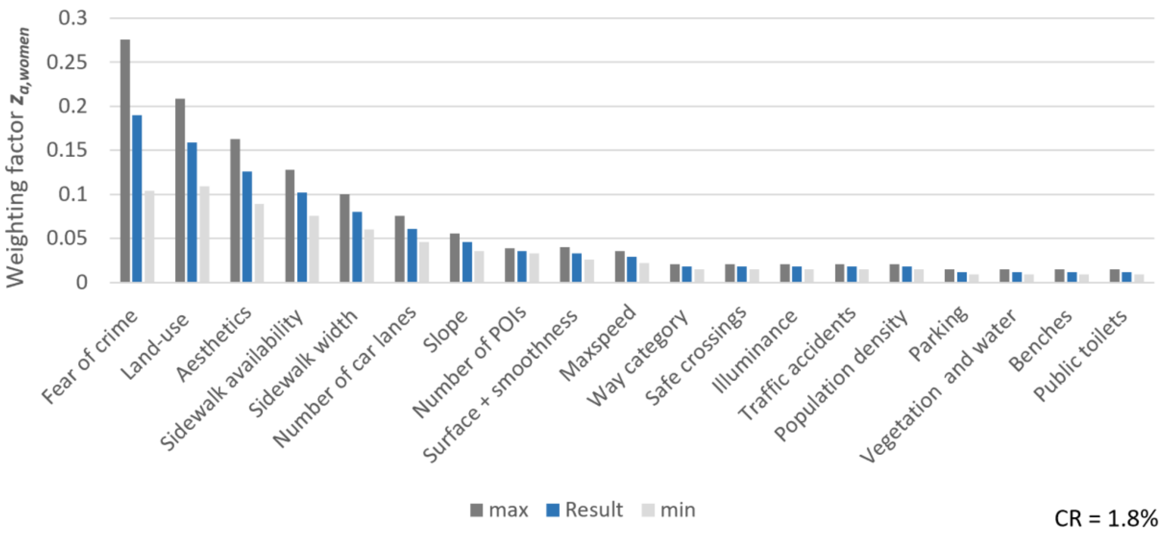


Figure 41: Key walkability attributes for women and their weights

7.3.2.4. Wheelchair users

Disability is a complex and multi-dimensional concept (Eurostat 2021). About 15% of the world's population is currently affected by disability. People with disabilities are defined as "those who have long-term physical, mental, intellectual or sensory impairments which in interaction with various barriers may hinder their full and effective participation in society on an equal basis with others" (European Commission 2010). In this research, we focus on wheelchair users as a sample user group. Wheelchair users have diverse abilities and moving speeds. For manual wheelchairs, movement speed varies from 0.48 m/s for older people to 0.8 m/s for athletes. The average speed is about 0.65 m/s (Sonenblum, Sprigle, and Lopez 2012). Infrastructural quality and comfort are the most important attributes for wheelchair users. Here the priorities are sidewalks free of barriers (Mackett, Achuthan, and Titheridge 2008; Mrak et al. 2019; Beale et al. 2006; Matthews et al. 2003; Berlin Senate Department for Urban Development 2011), of sufficient width (Mackett, Achuthan, and Titheridge 2008; Moura, Cambra, and Gonçalves 2017; Ferreira and da Penha Sanches 2007; Beale et al. 2006) that are well maintained with adequate surface materials and smoothness (Oeda, Sumi, and Vandebona 2003; Moura, Cambra, and Gonçalves 2017; Tseng 2020; Ferreira and da Penha Sanches 2007; Beale et al. 2006). Furthermore, safety at crossings (Lawson et al. 2022; Ferreira and da Penha Sanches 2007) is among the most important factors for these users (see *Figure 42*). Interestingly, the availability of benches is also regarded as important – not for the wheelchair users themselves but for people accompanying them.

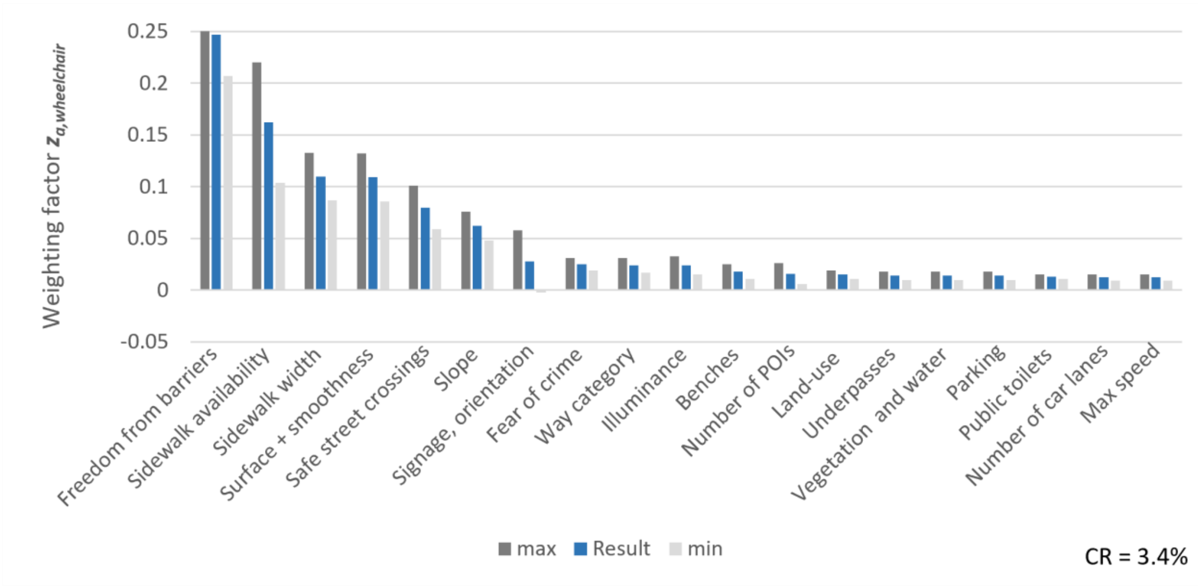


Figure 42: Key walkability attributes for wheelchair users and their weights

7.3.2.5. Summary of the weighting factors

Although the minimum and maximum values in *Figure 39* - *Figure* 42 show large deviations in some cases, the overall trend of the attribute importance is clearly recognisable. When comparing the resulting weighting factors between the different user groups, it is evident that there is a difference in the reported perception of the walkability attributes. The weighting factors resulting from the AHP method are summarised in *Table 17*. As no spatial data was available for some of these attributes (highlighted in grey), the attribute list was reduced accordingly and the weighting factors were adjusted. In order to prevent the (un)availability of data from distorting the results, the previously determined weighting factors of the categories were retained and only the weighting factors of the attributes were changed. The factors of the unavailable attributes were assigned to the closest proxies (highlighted in blue). For example, no specific data set was available for vegetation and water, but the land use data set contained some information on parks and green spaces. Therefore, these two attributes were addressed together.

Table 17: Summary of the weighting factors per attribute and user group

Walkability Categories	Attributes a	Weighting factors $z_{a,u}$ per user group u							
		Children		Seniors		Women		Wheelchair users	
Infrastructural quality and comfort	Way category	0.297	0.027	0.502	0.061	0.279	0.018	0.742	0.024
	Sidewalk availability		0.164		0.211		0.102		0.162
	Sidewalk width		0.027		0.102		0.080		0.110
	Slope		0.010		0.050		0.046		0.062
	Surface + smoothness		0.029		0.049		0.033		0.109
	Signage, orientation		0.000		0.000		0.000		0.028
	Freedom from barriers		0.040		0.029		0.000		0.247 (+ 0.028)
Traffic safety and road influences	Number of car lanes	0.454	0.032	0.303	0.081	0.138	0.061	0.119	0.0125
	Max speed		0.032		0.081		0.029		0.0125
	Safe street crossings		0.195		0.133		0.018		0.080
	Traffic accidents		0.177		0.000		0.018		0.000
	Parking		0.018		0.008		0.012		0.014
Security	Illuminance	0.066	0.018 (+ 0.0145)	0.135	0.009	0.208	0.018 (+ 0.095)	0.063	0.024 (+ 0.0125)
	Fear of crime		0.029		0.000		0.190		0.025
	Underpasses		0.019 (+ 0.0145)		0.126		- (+ 0.095)		0.014 (+ 0.0125)
Environment and liveliness	Population density	0.183	0.051	0.035	0.000	0.351	0.018	0.045	0.000
	Aesthetics		0.000		0.000		0.126		0.000
	Land use		0.099 (+ 0.033)		0.000 (+ 0.020)		0.159 (+ 0.126 + 0.012)		0.015 (+ 0.014)
	Vegetation and water		0.033		0.020		0.012		0.014
	Number of POIs		0.000		0.015		0.036		0.016
Urban equipment	Benches	0	0.000	0.025	0.013	0.024	0.012	0.031	0.018
	Public toilets		0.000		0.012		0.012		0.013

No data available (see *Table 16*)	
Serves as proxy for another attribute (indicated through arrow)	

Only the attributes with available data are taken into account in the remaining steps of this study.

7.3.3. Walkability scores for the case study

For the calculation of walkability scores, first, all *attribute values* that occur in the study area are translated into *attribute scores* s_a. The results are presented in *Appendix 2*. The walkability scores per user group are derived by multiplying the *attribute scores* s_a by the respective *weighting factors* $z_{a,u}$. The results are shown in *Figure 43*. Street level images were reviewed to verify the results.

Figure 43: Walkability scores

7.3.4. PAW calculation

By using the walkability scores as impedance factors, representing the perceived walking time, the PAW is calculated for typical locations of interest. The results are visualised in *Figure 44*. The numbers indicate the accessible population within each isochrone.

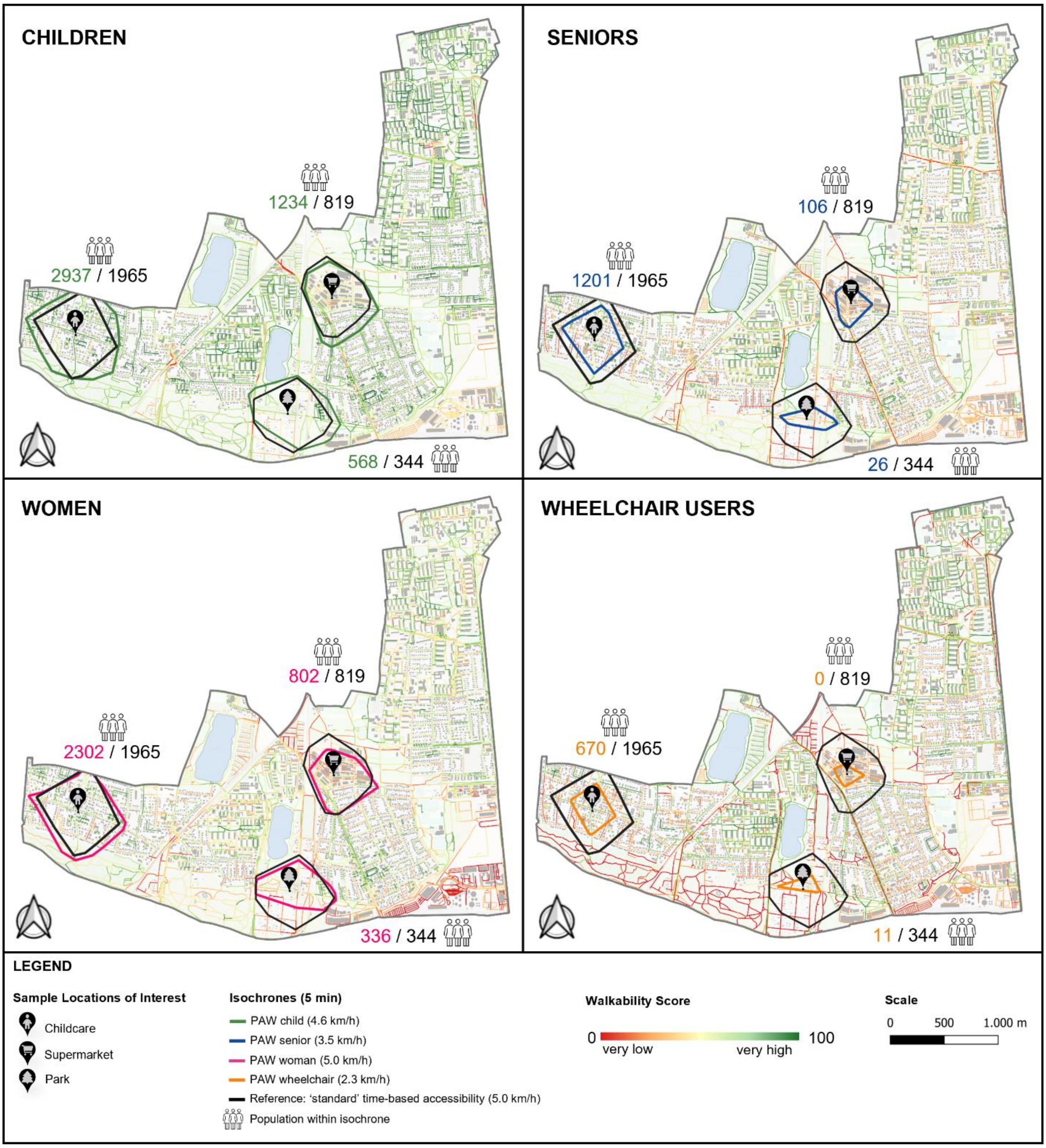


Figure 44: PAW for typical locations of interest

It is apparent that the perceived walking accessibility differs considerably for different user groups and does not match the 'standard' time-based accessibility that is usually used in studies, which confirms our hypothesis (cf. *Section 7.1.4*). The speed of wheelchair users is the slowest, which leads to comparably small isochrones and the result that not a single person with this user profile can reach the sample location of the supermarket within 5 minutes. However, even for women walking at the same speed as the 'standard', the isochrones are reduced in size – in areas where walkability according to their perception is low. On the other hand, in some areas where walkability is high, the isochrone size increases. This represents the fact that people are willing to walk longer distances if the environment is attractive and the conditions are good, and shows that accessibility levels are not just overestimated (see Curl, Nelson, and Anable (2015); J. Ryan and Pereira (2021)), but in some locations with a very attractive environment also underestimated. The isochrone size does thereby not directly reflect the accessible population, as in some areas (e.g. industrial areas and green spaces) no residents can be found.

7.3.5. Evaluation

Table 18 shows which of the recommendations for analysing pedestrian accessibility by Merlin and Jehle (2023) were implemented in PAW.

Table 18: Juxtaposition of recommended practice and PAW

Component	Current practice	Recommended practice	Implemented in PAW
Transport	Roadway network	Pedestrian network, including micro elements	Yes
Land-use	Administrative zones as origins / specific destination types	Buildings or grid-type zones as origins / specific destination types + land use influences on attractiveness	Partly via land use influences on attractiveness
Individual	All persons the same	Distinct population segments	Yes
Temporal	Not considered	Consider the Effect of Weather and Nighttime	Partly via “security” aspects (illuminance)
Impedance	Distance	(Perceived) Time	Yes
Objective vs. perceived	Objective	Imputed Perception	Yes

7.4. Discussion

The main shortcoming of previous calculated accessibility analyses was that they did not match with the perceived accessibility (Curl, Nelson, and Anable 2015; Damurski, Pluta, and Zipser 2020; Gebel et al. 2011; Jehle et al. 2022; Lättman, Olsson, and Friman 2018; McCormack et al. 2008; Pot, van Wee, and Tillema 2021; J. Ryan and Pereira 2021; M. Ryan et al. 2016; van der Vlugt, Curl, and Wittowsky 2019). To reduce this mismatch, we developed PAW, which includes user-specific walking needs and preferences in accessibility analyses. We worked with imputed perceptions, which we consider as the bridge between calculated and perceived accessibility (see *Figure 45*).

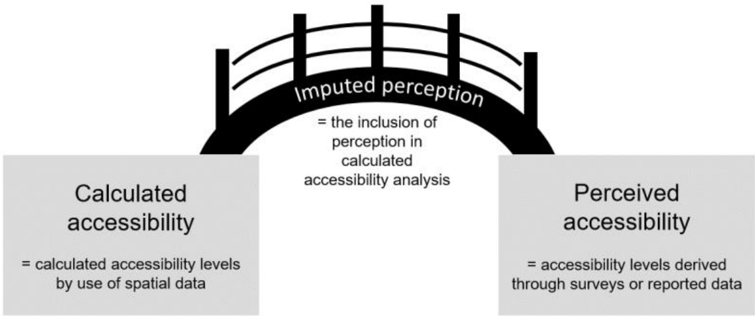


Figure 45: Bridging the gap between calculated and perceived accessibility

Imputed perceptions combine the advantages of both approaches: they use the insights from perceived accessibility studies and apply them to the spatial data. This allows more realistic accessibility analyses to be conducted for larger study areas that cannot normally be covered by surveys. In this way, the individual component of accessibility, which has been neglected for a long time (Merlin and Jehle 2023), is taken into account. To do this, we conceptualised the capability approach, which is tightly intertwined with the individual component of accessibility (Vecchio and Martens 2021), by examining whether intrinsic capabilities match external conditions. In the field of walkability, similar approaches have been used (Blečić et al. 2015; Fancello, Congiu, and Tsoukiàs 2020; Reyer et al. 2014), however, we went one step further and linked this to the perceived walking accessibility of different user groups. This follows a similar logic to the approach of Gaglione, Cottrill, and Gargiulo (2021) but considers a higher number of walkability attributes and includes additional user groups.

While PAW is not proven to be more advanced than current practice, it at least addresses most of the shortcomings identified. Although PAW as a methodological approach sounds promising and appears to be more realistic than 'standard' time-based accessibility analyses, there are three main points that need to be discussed.

7.4.1. Not all persons are the same

We used a technical approach by making perceptions quantifiable. We were pigeonholing people and assigning them very granular numbers (for the weighting of the walkability attributes as well as for walking speed). This might be straightforward and easy to communicate but neglects the characteristics, needs and capabilities of individual persons in a categorised group. In reality, people (even within one 'user group') have a wide range of walking speeds and every single person has their own preferences. Also, some users are associated with more than one user group. However, in trying to quantify those needs and translate them into easily understandable measures, we somehow need to find a balance between detail and ease of implementation (Papa et al. 2015). Hence we picked four sample profiles, which we considered as relatable for everyone and provided insights into how their perceived walking accessibility differs from the 'standard' time-based accessibility. The results revealed that especially for wheelchair users and for seniors, accessibility levels are overestimated in 'standard' time-based accessibility analyses. When their needs are not met, their perceived accessibility decreases significantly. In future, the here developed methodological approach can be further refined and transferred to further user groups. Since walkability needs differ not only on the basis of personal characteristics, but also depending on the purpose of the trip (Erath et al. 2015; Grob and Michel 2011; De Vries et al. 2010; Habibian and Hosseinzadeh 2018; Sabzali Yameqani and Alesheikh 2019) and the time of day (Jehle et al. 2022), categorisation based on these factors could also be useful.

7.4.2. Negotiable factors vs. non-negotiable factors

We used an additive method that calculates the total walkability score by building the sum of the weighted attribute score. While this approach is rather simple and thus easy to understand, in some regards it might be too simplified. For example, if the freedom of barriers is not given on a certain path, it is actually unusable for a wheelchair user. So, in fact, the result should be "0", but if other walkability attributes score high, the overall walkability score will still receive some points. Chan, Schwanen, and Banister (2021) therefore suggested that some attributes are negotiable and lower scores can be compensated by, and traded against, higher scores on others. But some attributes may be so important to certain people that they act as hard and non-negotiable constraints. The here developed measure approach is currently not able to represent such non-negotiable constraints.

Furthermore, we used the same walkability scale 0-100 for all user groups. But while a low score for wheelchair users could mean that they cannot move on this path because of physical barriers, a low score for women (e.g. as shown in *Figure 43*) "only" means that it's inconvenient, so they are physically still able to move but may have perceptual barriers, which, in effect, might also prevent them from walking. Overall, the needs are of different natures and the results of the different user groups are not per se comparable. However, they can help to create awareness of the needs and perceptions of different groups.

7.4.3. Location matters

Interestingly, from the maps in *Figure 43* and *Figure 44*, women seem to be more vulnerable than children in this study area. However, this result may not be per se transferable to other locations as the spatial characteristics have a high impact on the results. Thus, this effect may be caused by the chosen study area as for children, traffic safety is the biggest issue, and the chosen study area is largely traffic calmed. For women, environment and liveliness is the most important walkability category, which in this area has rather low scores. The chosen study area is also completely flat, which makes the attribute slope irrelevant. Thus, for other study areas, the results may differ – depending both on the place but also on the people. Especially in other countries, the walking conditions, but also the culture, behaviour and perception of people may be very different, which could lead to different results.

As there is no comprehensive study on the walkability perceptions of different user groups in Munich, we used literature from all over the world as input data for the AHP method. But the results of the same walkability survey could be very different for different places in the world, thus, the application of the results in the Munich context may not be accurate (cf. *Simpson's paradox:* when we aggregate data, we also lose specificity). When transferring this method to another study area, we recommend adapting it to the local context and using walkability studies from near-by or comparable locations as input data for the weighting schema.

7.4.4. The model is only as good as the input data

The PAW calculation requires a large amount of data – data on the importance of each walkability attribute per user group in order to calculate the weighting schema as well as spatial data for the study area. Although we picked a study area with high data availability, for some attributes, such as crime rates, no data was available. In addition, the presence of green and blue infrastructure was only included to a limited extent. For example, no information on shade and microclimate was available. The lack of certain data sets can have a crucial impact on the results because the model can only be as good as the input data. Therefore, it only makes sense to transfer the PAW to study areas for which at least a moderate amount of spatial data is available.

Moreover, the weighting schema is biased by existing studies of different authors in different contexts, which are naturally based on different setups, methods, assumptions and sample sizes. Thus, for example, the weighting factors for some attributes may be zero because these attributes were excluded from the outset in existing studies and therefore no evidence on their importance is available. Also, if one of the input studies contains a faulty value, the fault is propagated here.

7.5. Conclusion

This work aimed to contribute to the ongoing attempt of bridging the gap between calculated and perceived accessibility. Therefore, a new methodological approach (PAW) was developed, which considers user-specific walkability needs and people's perceptions in walking accessibility analyses. The juxtaposition of the method with the recommended practice of Merlin and Jehle (2023) shows that for the transport component, the individual component, the impedance calculation and the measure type, the recommended practice was fulfilled. For the land-use and temporal component, further adjustments need to be made.

The method was applied for four sample user groups: children, seniors, women, and wheelchair users. Part of this study was also to gain insights into the walkability differences between the various user groups. Interestingly, the importance per walkability attribute differs significantly between each of the user groups. For seniors and wheelchair users, who can both be regarded as, to some extent, mobility-impaired, the infrastructural conditions were the most important. For women, environmental and security factors were found to be the most relevant, which have more of a psychological impact. For children, traffic safety is the most important factor.

The result is not a universal weighting schema for the user-specific walkability attributes, but an example of how these can potentially be integrated in accessibility analyses via imputed perceptions. With the assumption that a pedestrian network that is suitable for the most vulnerable users will be suitable for everyone else, PAW for vulnerable user groups can help planners to design cities that are walkable for all. With increasing global data availability, PAW can be transferred to study areas worldwide and applied to other user groups.

The developed PAW was applied to one study area within Munich for testing the methodology. As a logical outcome of the differences in the importance of the walkability attributes, the perceived walking accessibility also shows marked differences between the user groups. The comparison with ‘standard’ time-based isochrones and the accessible population within the isochrones reveals that the perceived accessibilities of these user groups do not match the results of solely time-based calculations focused on an average user, confirming our hypothesis (cf. *Section 7.1.4*). The results show differences in both directions: in areas where walkability is low, the PAW isochrone is smaller, but in some areas where walkability is high, the PAW isochrone is larger. In addition to walkability levels, the walking speed also has a high influence on the accessibility of different user groups. At the same time, the size of the isochrone does not directly reflect the accessible population, as it also depends on population density.

7.5.1. Limitations and further research

This study adds to the attempts of Amaya et al. (2022) and Gaglione, Cottrill, and Gargiulo (2021) to provide more realistic walking accessibility analyses by combining the three components – accessibility, walkability and integration of user needs. Although the number of walkability attributes included in the study could be increased, information on some important attributes, such as crime rate, was still missing. When applying the method to other study areas, the weighting schema can be refined while adjusting it to the local context. In addition, we recommend that the developed PAW method be subjected to further testing and comparison with ‘standard’ time-based accessibility measures in order to ascertain whether the results are indeed more realistic.

Furthermore, it needs to be highlighted that every person is different and the sample user groups we picked here are just an approximation of the ‘average’ needs of persons with certain characteristics in terms of age, gender and capabilities. For the intended aim of PAW, to serve as methodological approach for a decision support system in planning processes, this categorisation may be beneficial for highlighting shortcomings in overall pedestrian accessibility. However, for specific planning questions, it is inevitable that the method will have to be expanded to further user groups, such as teenagers or visually impaired persons. In addition, further user groups in terms of trip purpose, and time of day, week and year might be useful. As peoples’ needs, preferences and perceptions also depend on the local conditions and culture, the developed weighting schema should be adapted to the local context of the study by ideally only using AHP input values that are derived from in situ surveys in this specific location. Through such surveys, real reported statements on the perceptions for specific locations in the study area could also be gathered and included in the resulting accessibility maps to enhance empathy and understanding of the needs of the vulnerable user groups.

The PAW methodology, which was developed here for isochrones, can also be transferred to heatmaps. This would even allow for the implementation of different walking distance thresholds and decay functions for different user groups, as was done by García-Palomares, Gutiérrez, and Cardozo (2013) and Arranz-López et al. (2019). To fully represent the land-use component, further focus on the destination potential is needed (e.g. by analysing how many children live within reach). On the temporal component, the consideration of weather and nighttime should be further assessed. To also represent hard constraints, the method should be further enhanced to differentiate between negotiable factors and non-negotiable factors.

7.6. Appendix

Appendix 1: References and AHP results per user group

		Children			Seniors			Women			Wheelchair Users		
	Attributes	**References**	**Average priority order**	**AHP weight**	**References**	**Average priority order**	**AHP weight**	**References**	**Average priority order**	**AHP weight**	**References**	**Average priority order**	**AHP weight**
Infrastructural quality and comfort	Sidewalk availability	(Moura, Cambra, and Gonçalves 2017; De Vries et al. 2010; He et al. 2021; Rosenberg et al. 2009; Zhao et al. 2021; S. Lee et al. 2020)	2	0.164	(Distefano, Pulvirenti, and Leonardi 2021; Pulvirenti, Distefano, and Leonardi 2020; Patterson and Chapman 2004; Kealey et al. 2005; Strath, Isaacs, and Greenwald 2007; WHO 2007)	1	0.211	(Clifton and Livi 2005; Pelclová, Frömel, and Cuberek 2013; Adlakha and Parra 2020; Nichani et al. 2019; Gorrini et al. 2021; Yildirim, Ince, and Muftuler 2012)	4	0.102	(Moura, Cambra, and Gonçalves 2017; Berlin Senate Department for Urban Development 2011; Tseng 2020; Lawson et al. 2022; Ferreira and da Penha Sanches 2007; Mrak et al. 2019; Beale et al. 2006; Matthews et al. 2003; Rosenberg et al. 2013)	2	0.162
	Way category	(De Vries et al. 2010; He et al. 2021; Rosenberg et al. 2009; Timperio et al. 2006)	6	0.027	(Pulvirenti, Distefano, and Leonardi 2020; WHO 2007)	5	0.061	(Adlakha and Parra 2020; Pelclová, Frömel, and Cuberek 2013; Yildirim, Ince, and Muftuler 2012)	11	0.018	(Berlin Senate Department for Urban Development 2011; Tseng 2020; Lawson et al. 2022; Beale et al. 2006)	8	0.024
	Sidewalk width	(Zhao et al. 2021)	6	0.027	(Pulvirenti, Distefano, and Leonardi 2020; Distefano, Pulvirenti, and Leonardi 2021; WHO 2007)	3	0.102	(Sethi and Vélez-Duque 2021; Gorrini et al. 2021; Pelclová, Frömel, and Cuberek 2013; Nichani et al. 2019; Yildirim, Ince, and Muftuler 2012)	5	0.080	(Moura, Cambra, and Gonçalves 2017; Berlin Senate Department for Urban Development 2011; Tseng 2020; Rosenberg et al. 2013; Ferreira and da Penha Sanches 2007; Beale et al. 2006; Matthews et al. 2003; Mackett, Achuthan, and Titheridge 2008)	3	0.110
	Slope	(Timperio et al. 2006)	7	0.010	(Pulvirenti, Distefano, and Leonardi 2020; Distefano, Pulvirenti, and Leonardi 2021; WHO 2007)	6	0.050	(Golan et al. 2019; Pelclová, Frömel, and Cuberek 2013; Adlakha and Parra 2020; Nichani et al. 2019; Yildirim,	7	0.046	(Berlin Senate Department for Urban Development 2011; Tseng 2020; Rosenberg et al. 2013; Beale et al. 2006; Matthews et al. 2003; Mackett, Achuthan, and Titheridge 2008)	5	0.062

		Children			Seniors			Women			Wheelchair Users		
	Attributes	**References**	**Average priority order**	**AHP weight**	**References**	**Average priority order**	**AHP weight**	**References**	**Average priority order**	**AHP weight**	**References**	**Average priority order**	**AHP weight**
								Ince, and Muftuler 2012)					
	Surface + smoothness	(He et al. 2021; Zhao et al. 2021; S. Lee et al. 2020)	5	0.029	(Pulvirenti, Distefano, and Leonardi 2020; Distefano, Pulvirenti, and Leonardi 2021; WHO 2007)	6	0.049	(Golan et al. 2019; Pelclová, Frömel, and Cuberek 2013; Adlakha and Parra 2020; Nichani et al. 2019; Yildirim, Ince, and Muftuler 2012)	9	0.033	(Moura, Cambra, and Gonçalves 2017; Berlin Senate Department for Urban Development 2011; Tseng 2020; Rosenberg et al. 2013; Ferreira and da Penha Sanches 2007; Beale et al. 2006; Matthews et al. 2003)	3	0.109
	Segregation from bicycles	-	-	-	-	-	-	-	-	-	-	-	-
	Signage, orientation	-	-	-	-	-	-	-	-	-	(Moura, Cambra, and Gonçalves 2017; Berlin Senate Department for Urban Development 2011; Matthews et al. 2003)	6	0.028
	Freedom from barriers	(Moura, Cambra, and Gonçalves 2017; He et al. 2021; Zhao et al. 2021; S. Lee et al. 2020)	5	0.040	(Pulvirenti, Distefano, and Leonardi 2020; WHO 2007)	7	0.029	(Golan et al. 2019; Gorrini et al. 2021)	11*	-	(Moura, Cambra, and Gonçalves 2017; Berlin Senate Department for Urban Development 2011; Tseng 2020; Rosenberg et al. 2013; Mrak et al. 2019; Beale et al. 2006; Matthews et al. 2003; Mackett, Achuthan, and Titheridge 2008)	1	0.247
	Shelter, shade	-	-	-	-	-	-	-	-	-	-	-	-
Traffic safety and road influences	Spatial separation of footpath from road	-	-	-	-	-	-	-	-	-	-	-	-
	Number of car lanes	(Zhao et al. 2021; Molina-García et al. 2020; Jamme, Bahl, and Banerjee 2018; Timperio et al. 2006)	5	0.032	(Saelens et al. 2003; Distefano, Pulvirenti, and Leonardi 2021; Aronson and Oman 2004; Lockett 2005; Pulvirenti, Distefano, and Leonardi 2020; Patterson and	4	0.081	(Golan et al. 2019; Gorrini et al. 2021; Clifton and Livi 2005; Pelclová, Frömel, and Cuberek 2013; Adlakha and Parra 2020; Nichani et al. 2019; Yildirim,	6	0.061	(Berlin Senate Department for Urban Development 2011; Tseng 2020; Rosenberg et al. 2013; Lawson et al. 2022)	10	0.0125

		Children			Seniors			Women			Wheelchair Users		
	Attributes	**References**	**Average priority order**	**AHP weight**	**References**	**Average priority order**	**AHP weight**	**References**	**Average priority order**	**AHP weight**	**References**	**Average priority order**	**AHP weight**
					Chapman 2004; Kealey et al. 2005; Lees et al. 2007; Strath, Isaacs, and Greenwald 2007)			Ince, and Muftuler 2012)					
	Traffic load	-	-	-	-	-	-	-	-	-	-	-	-
	Proportion of heavy goods vehicles	-	-	-	-	-	-	-	-	-	-	-	-
	Noise	-	-	-	-	-	-	-	-	-	-	-	-
	Emissions / air quality	-	-	-	-	-	-	(Adlakha and Parra 2020)	12*	-	-	-	-
	Max speed	(Zhao et al. 2021; Molina-García et al. 2020; Jamme, Bahl, and Banerjee 2018; Timperio et al. 2006)	5	0.032	(Distefano, Pulvirenti, and Leonardi 2021; Pulvirenti, Distefano, and Leonardi 2020; Patterson and Chapman 2004; Strath, Isaacs, and Greenwald 2007; Aronson and Oman 2004; Lockett 2005; Kealey et al. 2005; Lees et al. 2007; Saelens et al. 2003)	4	0.081	(Gorrini et al. 2021; Clifton and Livi 2005; Pelclová, Frömel, and Cuberek 2013; Adlakha and Parra 2020; Nichani et al. 2019; Yildirim, Ince, and Muftuler 2012)	10	0.029	(Berlin Senate Department for Urban Development 2011; Tseng 2020; Rosenberg et al. 2013; Lawson et al. 2022)	10	0.0125
	Safe street crossings	(Moura, Cambra, and Gonçalves 2017; De Vries et al. 2010; He et al. 2021; Zhao et al. 2021; Molina-García et al. 2020; Jamme, Bahl, and Banerjee 2018; Timperio et al. 2006)	1	0.195	(Distefano, Pulvirenti, and Leonardi 2021; Aronson and Oman 2004; Lockett 2005; Kealey et al. 2005; WHO 2007; Michael, Green, and Farquhar 2006; Kerr, Rosenberg, and Frank 2012)	2	0.133	(Gorrini et al. 2021; Pelclová, Frömel, and Cuberek 2013; Nichani et al. 2019; Yildirim, Ince, and Muftuler 2012)	11	0.018	(Moura, Cambra, and Gonçalves 2017; Berlin Senate Department for Urban Development 2011; Tseng 2020; Rosenberg et al. 2013; Lawson et al. 2022; Ferreira and da Penha Sanches 2007; Beale et al. 2006; Matthews et al. 2003; Mackett, Achuthan, and Titheridge 2008; Mrak et al. 2019)	4	0.080
	Traffic accidents	(Moura, Cambra, and Gonçalves 2017; De Vries et al. 2010; He et al.	2	0.177	-	-	-	(Gorrini et al. 2021; Clifton and Livi 2005)	11	0.018	-	-	-

		Children			Seniors			Women			Wheelchair Users		
	Attributes	**References**	**Average priority order**	**AHP weight**	**References**	**Average priority order**	**AHP weight**	**References**	**Average priority order**	**AHP weight**	**References**	**Average priority order**	**AHP weight**
		2021; Zhao et al. 2021; Molina-García et al. 2020; Jamme, Bahl, and Banerjee 2018; Timperio et al. 2006)											
	Parking	(De Vries et al. 2010; Zhao et al. 2021; Molina-García et al. 2020)	6	0.018	(Distefano, Pulvirenti, and Leonardi 2021; Pulvirenti, Distefano, and Leonardi 2020; WHO 2007)	13	0.008	(Golan et al. 2019)	12	0.012	(Tseng 2020)	10	0.014
Security	Illuminance	(De Vries et al. 2010; Jamme, Bahl, and Banerjee 2018; Timperio et al. 2006)	6	0.018	(Distefano, Pulvirenti, and Leonardi 2021; Pulvirenti, Distefano, and Leonardi 2020; WHO 2007)	12	0.009	(Clifton and Livi 2005; Yildirim, Ince, and Muftuler 2012; Sethi and Vélez-Duque 2021)	11	0.018	(Berlin Senate Department for Urban Development 2011; Tseng 2020; Rosenberg et al. 2013; Mackett, Achuthan, and Titheridge 2008)	8	0.024
	Fear of crime	(He et al. 2021; Rosenberg et al. 2009; S. Lee et al. 2020; Jamme, Bahl, and Banerjee 2018)	5	0.029	-	-	-	(Golan et al. 2019; Hille 1999; Loukaitou-Sideris 2014; Pelclová, Frömel, and Cuberek 2013; Adlakha and Parra 2020; Nichani et al. 2019; Yildirim, Ince, and Muftuler 2012; Clifton and Livi 2005)	1	0.19	(Moura, Cambra, and Gonçalves 2017; Berlin Senate Department for Urban Development 2011; Rosenberg et al. 2013; Mackett, Achuthan, and Titheridge 2008)	7	0.025
	Underpasses	(He et al. 2021; Jamme, Bahl, and Banerjee 2018)	6	0.019	(Distefano, Pulvirenti, and Leonardi 2021; Michael, Green, and Farquhar 2006; WHO 2007; Kerr, Rosenberg, and Frank 2012)	2	0.126	-	-	-	(Moura, Cambra, and Gonçalves 2017)	10	0.014

		Children			Seniors			Women			Wheelchair Users		
	Attributes	**References**	**Average priority order**	**AHP weight**	**References**	**Average priority order**	**AHP weight**	**References**	**Average priority order**	**AHP weight**	**References**	**Average priority order**	**AHP weight**
Environment and liveliness	Population density	(He et al. 2021; Rosenberg et al. 2009; Molina-García et al. 2020; Ikeda et al. 2018)	4	0.051	-	-	-	(Pelclová, Frömel, and Cuberek 2013; Adlakha and Parra 2020)	11	0.018	-	-	-
	Cleanliness	-	-	-	-	-	-	-	-	-	-	-	-
	Vegetation and water	(De Vries et al. 2010; He et al. 2021; Molina-García et al. 2020; Jamme, Bahl, and Banerjee 2018; S. Lee et al. 2020)	5	0.033	(Strath, Isaacs, and Greenwald 2007; Kealey et al. 2005; Michael, Green, and Farquhar 2006; Lees et al. 2007; Saelens et al. 2003; WHO 2007)	8	0.020	(Golan et al. 2019; Gorrini et al. 2021; Sethi and Vélez-Duque 2021)	12	0.012	(Berlin Senate Department for Urban Development 2011)	10	0.014
	Microclimate / inner-city aeration	-	-	-	-	-	-	-	-	-	-	-	-
	Land use	(Moura, Cambra, and Gonçalves 2017; He et al. 2021; Rosenberg et al. 2009; Molina-García et al. 2020; S. Lee et al. 2020; Jamme, Bahl, and Banerjee 2018)	3	0.099	-	-	-	(Golan et al. 2019; Gorrini et al. 2021; Clifton and Livi 2005; Pelclová, Frömel, and Cuberek 2013; Adlakha and Parra 2020; Nichani et al. 2019; Yildirim, Ince, and Muftuler 2012)	2	0.159	(Moura, Cambra, and Gonçalves 2017; Tseng 2020)	10	0.015
	Number of POIs	(Moura, Cambra, and Gonçalves 2017; He et al. 2021; Rosenberg et al. 2009; Jamme, Bahl, and Banerjee 2018)	7*		(Aronson and Oman 2004; Lockett 2005; Strath, Isaacs, and Greenwald 2007; Michael, Green, and Farquhar 2006)	9	0.015	(Gorrini et al. 2021; Pelclová, Frömel, and Cuberek 2013; Yildirim, Ince, and Muftuler 2012; Sethi and Vélez-Duque 2021)	8	0.036	(Moura, Cambra, and Gonçalves 2017)	10	0.016
	Aesthetics	-	-	-	-	-	-	(Golan et al. 2019; Clifton and Livi 2005; Pelclová, Frömel, and Cuberek 2013; Adlakha	3	0.126	-	-	-

		Children			Seniors			Women			Wheelchair Users		
	Attributes	**References**	**Average priority order**	**AHP weight**	**References**	**Average priority order**	**AHP weight**	**References**	**Average priority order**	**AHP weight**	**References**	**Average priority order**	**AHP weight**
								and Parra 2020; Yildirim, Ince, and Muftuler 2012)					
	Pedestrian flow rate	-	-	-	-	-	-	-	-	-	-	-	-
Urban equipment	Benches	-	-	-	(Michael, Green, and Farquhar 2006; WHO 2007)	10	0.013	(Sethi and Vélez-Duque 2021)	12	0.012	(Moura, Cambra, and Gonçalves 2017)	9	0.018
	Bins	-	-	-	-	-	-	(Sethi and Vélez-Duque 2021)	11*	-	(Tseng 2020)	10*	-
	Public toilets	-	-	-	(WHO 2007)	11	0.012	(Sethi and Vélez-Duque 2021)	12	0.012	(Moura, Cambra, and Gonçalves 2017; Matthews et al. 2003)	10	0.013
	Water fountains	-	-	-	-	-	-	(Sethi and Vélez-Duque 2021)	11*	-	-	-	-

*Not considered for AHP evaluation

Appendix 2: Attribute values and scores

Walkability Categories	Attributes	Attribute values[11]	Attribute scores s_a
Infrastructural quality and comfort	Way category	living_street ; pedestrian ; footway	100
		residential	90
		cycleway	70
		path ; road	50
		tertiary ; tertiary_link ; unclassified ; service	30
		track ; secondary ; secondary_link ; bridleway	20
		steps ; construction ; motorway ; motorway_link ; primary ; primary_link ; trunk; trunk_link ; proposed	0
	Sidewalk availability	yes ; both	100
		right ; left	80
		no	0
	Sidewalk width	> 3m	100
		1.5 – 3m	50
		≤ 1.5 m	20
	Slope	≤1%	100
		1 - 2 %	90
		2 - 3 %	80
		3 - 4 %	70
		4 - 5 %	60
		5 - 6 %	50
		6 - 7 %	40
		7 - 8 %	30
		8 - 9 %	10
		> 9	0
	Surface	paved ; asphalt ; concrete ; concrete:lanes ; paving_stones ; cobblestone:flattened	100
		stone ; sandstone; sett ; metal ; unhewn_cobblestone ; cobblestone	80
		unpaved ; compacted	50
		fine_gravel ; metal_grid ; gravel ; pebblestone ; rock ; wood ; ground ; dirt ; earth ;	30
		grass ; grass_paver ; mud ; sand	20
		grass_paver	20
		no_data	50
	Smoothness	excellent ; very_good	100
		good	90
		intermediate	50
		bad ; very_bad	20
		horrible ; very_horrible	10
		impassable	0
	Freedom from barriers	yes	100
		limited	50
		no	0
		unclassified	50
Traffic safety and road influences	Number of car lanes	≤1	100
		>1-2	70
		>2-4	30
		>4	0
	Max speed	≤15	100
		>15-30	75
		>30-50	50
		>50-70	25
		>70	0

[11] Further information and explanation on the values from the OSM data sets can be found in the OSM Wiki (https://wiki.openstreetmap.org/wiki/Key:highway)

Walkability Categories	Attributes	Attribute values[11]	Attribute scores s_a
	Number of street crossings	-1[12]	100
		>2	100
		2	90
		1	50
		0	0
	Traffic accidents[13]	0	100
		1	60
		2	40
		>2	0
	Parking	off_street	0
		on_street	50
		no	100
Security	Illuminance	yes	100
		no	0
	Underpasses	no ; colonnade ; building_passage ; arcade	100
		yes	0
Environment and liveliness	Population density[14]	high	100
		medium	70
		low	30
		no	0
	Land use	community ; nature ; residential ; leisure ; water	100
		commercial	50
		agriculture	40
		transportation	20
		industrial	0
	Number of POIs[15]	no	0
		very_low	25
		low	50
		medium	75
		high	100
Urban equipment	Benches[16]	0	0
		1	50
		2	75
		>2	100
	Public toilets[17]	0	0
		≥1	100

If no data on a certain attribute was available, an average value of 50 was assumed.

[12] This value was assigned by us if the max speed is ≤ 30 km/h or the way category is ‘residential’ or ‘service’ as we assume that in these cases it is also possible to cross the street without having dedicated crossings.
[13] To project the accident data onto the paths, buffers of 30 m were created around the accident locations and intersected with the paths.
[14] Percentiles are used for the classification.
[15] To assign the number of POIs in the vicinity surrounding the paths, buffers of 50 m were created around the POIs and intersected with the paths. Percentiles are used for the classification.
[16] To assign the number of benches in the vicinity surrounding the paths, buffers of 30 m were created around the benches and intersected with the paths.
[17] To assign the number of public toilets in the vicinity surrounding the paths, buffers of 300m were created around the toilets and intersected with the paths.

Part III
Synthesis and conclusions

8. Synthesis and discussion

In *Chapters 4* to *7*, the four publications and their respective results were presented and discussed, while each paper contributed to a specific component of the dissertation. This chapter provides a summary and discussion of the findings for each of the three research questions.

8.1. RQ 1: Existing approaches

Which walking accessibility studies exist, what do they consider and what are they missing?

The systematic scoping review of the academic literature concerning pedestrian accessibility (see *Chapter 4*) revealed that there is a global interest in walking accessibility. Although it has not received as much attention as accessibility by private vehicle or public transit, the number of walking accessibility studies is steadily increasing since 1997. This increasing interest may be due to the improved utilisation of GIS, which are an essential instrument for almost all accessibility studies, and the increasing availability of detailed data on the walking infrastructure and the (built) environment. Thus, as Handy (2020) also stated in relation to accessibility measures in general (see *Section 2.3.2*), *Chapter 4* concludes that the time has come for walking accessibility measures as well.

There is no such thing as a universal construction manual of walking accessibility measures, so the structure of the methods varies according to the purpose of the study, the data availability and the gusto of the authors. However, some patterns on the consideration of the four accessibility components (*Section 8.1.1*), the used impedance (*Section 8.1.2*) and the measure approach (calculated vs. perceived; *Section 8.1.3*) were found. Additional findings on walkability measures from *Chapter 6* and beyond are presented in *Section 8.1.4*. The limitations are discussed in *Section 8.1.5.*

8.1.1. Four accessibility components

Ideally, all four components are considered in an accessibility measure (Geurs and van Wee 2013). This section summarises if and how each of the components are currently included in walking accessibility analyses and what should be improved in future measures.

Transport component: When analysing walking accessibility, the pedestrian network with all its elements and characteristics should be considered as transport component. In existing methods, the level of detail highly varies (see *Section 4.3.1*). While some measures simply take the linear distance between origin and destination (e.g. Anciaes, Nascimento, and Silva

2015) or use the roadway network (e.g. Saghapour, Moridpour, and Thompson 2019; Roblot et al. 2021), others consider the real pedestrian network with its microscale elements (e.g. Blečić, Cecchini, and Trunfio 2015; Amaya et al. 2022). Ideally, not only sidewalks (on both sides of the street) but also plazas, parks, shared-use paths, pedestrian bridges, underpasses, off-street paths, stairways, escalators, street crossings and interior corridors are taken into account. Furthermore, all the characteristics of the pedestrian infrastructure, such as slope, width, surface and the surrounding environment, should be mapped and included in the measure. They are not only affecting the walkability but are also tightly interwoven with the individual component. For example, when considering the accessibility needs of persons in wheelchairs, obstacles and surface unevenness become severe constraints that not only influence how attractive a path is but also if it is passable at all. Depending on the studied population group, different attributes are considered by the authors (see e.g. Laakso et al. 2013; Orellana et al. 2020; Amaya et al. 2022). However, overall, existing walking accessibility measures are currently far away from considering all influencing attributes. Hence, the walking infrastructure is not realistically represented. The biggest barrier is the limited data availability. Although OSM probably is the most complete global open data set for pedestrian networks, it still has many gaps, low completeness on the attributes and inhomogeneity in the mapping structure. Several researchers, therefore, use site visits, street view images, or aerial maps to enrich OSM and construct detailed pedestrian networks.

Land-use component: Through the land-use component, demand (origins) and opportunities (destinations) are modelled. As origin, mostly the population is considered (see *Section 4.3.2*). Some papers are less specific and consider either any building (e.g. Erath et al. 2017; Sun et al. 2015) or any possible location in the city (e.g. Arranz-López, Soria-Lara, and Ariza-Álvarez 2021; Roblot et al. 2021) as an origin. While in older studies mostly administrative zones were used as origins, the units become more and more fine-grained with more recent studies, driven by better data availability. Ideally, to be most accurate, individual housing entrances should be used as origins when using population as demand. As destinations, walking accessibility studies address a much greater range of destination types than is typically found for transit and car accessibility, where most studies focus on accessibility to jobs. The most common destinations analysed are a variety of POIs (e.g. health service facilities, schools, childcare facilities, shopping, recreational amenities, transit stops) and parks. Here, once more, the individual component also plays an important role, as each destination type may have distinct demographic segments that it attracts. Thus, it makes sense to analyse different destination types separately rather than aggregating them into a joint index (see *Section 4.4*). Ideally, also the attributes of the destinations (e.g. service frequency, opening hours, sales area) are taken into account as these are influencing the destination attractiveness. But land-use features not only create demand and opportunities, they also serve as features that effect the attractiveness of the transport component, i.e. the walking paths (cf. *Figure 5)*. A few studies (e.g. Broach and Dill 2016; D'Orso and Migliore 2018; Gaglione, Cottrill, and Gargiulo 2021) examined the influence of land use on the perceived impedance (see *Section 4.3.2*). Those ideally should be considered more in-depth in future studies to achieve comprehensive results.

Individual component: The individual component defines the needs, capabilities and preferences of persons. Although there is growing attention to the individual aspect of walking accessibility, most studies still consider the entire population as homogenous and do not take individual needs, capabilities and preferences into account. Nevertheless, some studies conduct user group specific analyses or compare the accessibility of different population groups (see *Section 4.3.3*). The population groups that have often been considered are older adults (e.g. Arranz-López, Soria-Lara, and Ariza-Álvarez 2021; Borowska-Stefańska and Wiśniewski 2017; Marquet, Bedoya, and Miralles-Guasch 2017) and those in wheelchairs (e.g. Church and Marston 2003; Laakso, Sarjakoski, and Sarjakoski 2011; Orellana et al. 2020). A few studies on children were found (Reyes, Páez, and Morency 2014; García-Palomares, Gutiérrez, and Cardozo 2013). Socioeconomic variables, such as income, vehicle ownership, and housing type, are also sometimes used to evaluate differences in pedestrian accessibility (e.g. Anciaes, Nascimento, and Silva 2015; Chandra, Jimenez, and Radhakrishnan 2017; Morar, Radoslav, and Spiridon 2014). Ideally, further population segments should be taken into account in accessibility analyses and their needs, capabilities and preferences should be reflected in the other accessibility components. Based on the personal characteristics, different destinations are of interest and different walking speeds and distance thresholds exist. Besides, each population group has specific needs and requirements for walking infrastructure in terms of safety, freedom from barriers, etc. To account for the individual component, the consideration of perceived route attractiveness factors as routing impedance seems a valid approach. At the same time, it does not seem reasonable for urban and transport planning to have a fully individualised approach to accessibility, as decision makers plan the built environment for general populations, not only for specific individuals (see *Section 4.4*). Rather, analyses disaggregated by population groups (e.g. children's accessibility to schools with particular emphasis on traffic safety, as done recently by Tavakoli et al. (2024)) may be beneficial for planners to highlight shortcomings in walking accessibility to essential amenities.

Temporal component: Temporal variations such as opening hours, climatic and nighttime conditions can be modelled via the temporal component. Among the four accessibility components, the temporal component is the one with clearly the least consideration in research and in practice (see *Section 4.3.4*). Only a few papers considered the effect of nighttime (Chandra, Jimenez, and Radhakrishnan 2017; Jehle 2020), variations in weather (Erath et al. 2015) and impacts of opening hours (Jehle 2020). However, climatic and light conditions have a huge impact on walking needs, and opening hours and service times clearly influence the accessible opportunities. Hence, the temporal component and its effects on the other components should ideally be considered in future walking accessibility analyses (see *Section 4.4)*.

8.1.2. Impedance

The impedance determines the resistance to walk from origin to destination. Existing studies most commonly use simple distance, measured on the pedestrian network, as impedance (see *Section 4.3.5*). In some cases, distance was enhanced to "effective" distance by considering aspects of transportation infrastructure such as slope (e.g. Blečić et al. 2013; D'Orso and Migliore 2018; Kuzmyak, Baber, and Savory 2006). Other researchers tried to incorporate perceived distance by adding impedances based on the quality of the path, assigning greater lengths to unpleasant routes (e.g. Blečić, Cecchini, and Trunfio 2018; Jang et al. 2020; Jonietz and Timpf 2012).

However, the second most common method for measuring impedance – travel time – may be a more advantageous unit of analysis (see *Section 4.4)*, as there is evidence that people can better relate to walking times than walking distances (Vale and Pereira 2017). Travel time is thereby computed based on distance and walking speed, having the advantage that different walking speeds for different population groups can be used, as e.g. done by Amaya et al. (2022) and Gaglione, Cottrill, and Gargiulo (2021). As for distance, the "effective" travel time can be calculated by increasing the walking time along particular segments due to slope or impediments (e.g. Amaya et al. 2022; Li et al. 2018; Tang et al. 2021). The impedance can be influenced by all four components, as well as interactions between the four components (see *Section 4.3.5*). So, to be more accurate, ideally, perceived travel time should be used as impedance by including the user's perceptions of path and environmental attractiveness (Boakye-Dankwa et al. 2019; Gaglione, Cottrill, and Gargiulo 2021). The perceptions were, thereby, e.g. conceptualised through behavioural analysis (Broach and Dill 2016) and surveys (Erath et al. 2015; Sun et al. 2015).

8.1.3. Calculated vs. perceived accessibility

Accessibility measures can be clustered in calculated and perceived approaches. In earlier stages of this dissertation (*Chapter 6*), the terms *objective* and *subjective* were used to describe the approach of accessibility measures. However, as all models and indicators are somehow generated by humans, they can never be fully *objective* (Haugen et al. 2012; J. Ryan and Pereira 2021; Schwanen and de Jong 2008). Thus, in the later stages of the dissertation (*Chapter 4*), the term *subjective accessibility* was replaced by *perceived accessibility*, as it is also used by the majority of the existing literature (e.g. Lättman, Olsson, and Friman 2018;

Pot, van Wee, and Tillema 2021; Mark Ryan et al. 2016; van der Vlugt, Curl, and Wittowsky 2019). As a counterpart, the author later (*Chapters 5 and 7*) also moved from the term *objective accessibility* to *calculated accessibility*, as recommended by Jean Ryan and Pereira (2021) and Pot, van Wee, and Tillema (2021).

Most of the existing walking accessibility studies focus on calculated accessibility (see *Section 4.3.6*). However, several studies have discovered a mismatch between calculated and perceived accessibility (Damurski, Pluta, and Zipser 2020; Curl, Nelson, and Anable 2015; Lättman, Olsson, and Friman 2018; M. Ryan et al. 2016; van der Vlugt, Curl, and Scheiner 2022). Similar discrepancies were also found in the Access to Rail project (see *Chapter 5*). Thus, in order to obtain realistic and holistic results, the perceptions should ideally be imputed in calculated accessibility measures based on empirical evidence from appropriate perceptual studies, thus using the advantages of both approaches (see *Section 4.4*). *Imputed perception* (in other words: ascribed perception) is a new term in the field of accessibility that evolved from *Chapter 4* and summarises comparable methodological approaches from other authors (e.g. Erath et al.'s (2017) "behaviorally calibrated" accessibility indicator and Amaya et al.'s (2022) "multivariate accessibility model"). In literature reviews, these methodological approaches are also often summarised with the term *combined measures* (see *Section 4.3.6*), but these also include other methods that do not follow the logic of imputed perceptions. Thus, to have a clear methodological distinction, the new term *imputed perceptions* was introduced.

Personal reflection

Despite occasional confusion when people hear the term *imputed perception* for the first time, I am still convinced that it embodies the implementation of perceptions into calculated measures very well, although it is a rather theoretical-methodological wording that indeed may be difficult to understand at first glance. Maybe there are better terms to describe this methodological approach. But so far, I did not come across one.

8.1.4. Additional findings on walkability measures

Walkability is influenced by numerous attributes. Walkability measures thereby try to capture those attributes and generate a walkability index. As for walking accessibility, the majority of the walkability measures follow a calculated approach. The second most common were perceived approaches. Here, as well a mismatch between their results was found (McGinn et al. 2007; Gebel et al. 2009; Golan et al. 2019). Some attempts were found that combine both approaches (e.g. Dannenberg, Cramer, and Gibson 2005), following the argumentation that some attributes are well suited to capture them "objectively" (e.g. sidewalk availability, sidewalk width, connectivity), while others are rather “subjective” by nature (e.g. architectural attractiveness).

While perceived measures are more accurate, they are resource-intensive to transfer to other study areas. Calculated measures are easier to transfer, but the existing measures are missing many important fine-scale attributes and individual perceptions. *Chapter 6* thus argues that future calculated measures should ideally be more comprehensive, including the whole variety of influencing attributes in a multi-criteria analysis and distinguishing between different population groups. With the increasing quality and availability of open data, also micro-features can therewith be integrated. As an analysis scale, street-level (e.g. 100m segments) seems the most appropriate as walkability conditions can change quite quickly. Furthermore, while some walkability measures also include accessibility components (such as destinations or path connectivity), the majority of the measures neglect them. This might be sufficient to increase

Personal reflection

When talking to different researchers and practitioners, and reading literature, I observed that the current lack of a generally accepted definition of walkability – which sometimes includes accessibility features and sometimes does not – results in people talking about the same term but actually meaning something different. This partially leads to misunderstandings and misinterpretation of research results. So ideally, a clear differentiation between walkability and walking accessibility should be made while highlighting that walkability is a part of accessibility but not the other way around.

undirected walking trips for leisure, but in the field of urban and transport planning, it is inevitable to acknowledge the interdependencies and close links between accessibility and walkability to achieve a comprehensive representation of walking needs.

8.1.5. Limitations

The review of existing accessibility measures was limited to three databases and English publications. The structured analysis was focused on the four accessibility components, the impedance calculation and calculated vs. perceived approaches. Further measure characteristics, such as measure type (e.g. cumulative-opportunities, gravity-based, topological or infrastructure-based measures) that were highlighted by many researchers as important characteristics of accessibility measures (e.g. Bhat et al. 2000; Vale, Saraiva, and Pereira 2016) were not assessed. Although all the papers were fully read by the author team, there might be further striking patterns beyond these topics that were overlooked.

The collection of walkability measures for review followed a less structured approach than the collection of accessibility measures. In addition, only publications in English and German were reviewed. It can, therefore, be assumed that the review is not complete.

8.2. RQ 2: Influencing attributes

Which attributes have an impact on perceived walking accessibility?

Curl (2018) stated the need for work directly comparing perceived and calculated accessibility for the same people or places to understand the differences. This was achieved in the Access to Rail project (see *Chapter 5*). Overall, there are many influencing factors which are easy to measure or capture objectively (e.g. footpath width, surface, lighting), but what cannot be calculated that easily are the perceptions. So to understand how different attributes of the environment and walking infrastructure are perceived by the people, surveys are needed. As part of this research, the attributes influencing perceived walking accessibility were analysed in different research activities (see *Section 3.2*). Among others, the methods and results of existing studies were analysed (see *Chapters 6 and 7*), and an own survey was conducted (see *Chapter 5*). In sum, a large number of influencing factors were identified. They can be clustered in: accessibility itself (*Section 8.2.1*), walkability attributes (*Section 8.2.2*), user characteristics (*Section 8.2.3*), geographical context (*Section 8.2.4*) and temporal changes (*Section 8.2.5)*. All of these influencing factors are complex in themselves and become even more complex when combined. The fact that perceived accessibility cannot be assessed directly, nor can the influencing attributes be analysed in isolation from each other, makes it difficult, if not impossible, to conclusively assess the exact impact per attribute. However, an enhanced understanding was generated in this work and will be presented in the following sections. The limitations are discussed in *Section 8.2.6*.

8.2.1. Accessibility itself

In the Access to Rail survey (see *Section 5.4*), respondents cited *time* as the most important factor in deciding whether or not to walk. Thus, good accessibility with proximity to destinations and network connectivity are prerequisites for walking. This finding is consistent with the hierarchy of walking needs (cf. *Figure 2*), where accessibility builds the foundation.

Personal reflection

The importance of accessibility may sound like common sense, but it took a research trip to Australia for me to be truly aware of it. Australia has the most walkable places, with well-designed public spaces and a wealth of lovingly crafted micro features that make walking pleasant, which I wanted to analyse during my stay. When I interviewed local practitioners and researchers, they confirmed my claim, but with an unexpected twist. They all said something like: “Yes, there are many places that are very attractive for walking. It only takes me 10 minutes by car to get there”. This opened my eyes to the bigger picture. In Europe, we are spoilt with historically grown city centres with a naturally high level of connectivity, diverse land use and, therefore, a rather high level of accessibility to daily services. The urban sprawl and car dependency that can be seen in many Australian cities made me realise again that it is the macro characteristics that matter first and that accessibility is the basic requirement that needs to be met to get people walking (without having to sit in a car first). It is not something we should take for granted, as it requires smart urban and transport planning to achieve.

Accessibility is strongly influenced by the opportunities available. Not only the location but also the characteristics of an opportunity determine its attractiveness. Interestingly, in the Access to Rail survey, the biggest weaknesses in the perceived accessibility of stations are found in the stations themselves. As the journey does not end at the station entrance, it is important that the destinations themselves (in this study the stations) are attractive and meet people’s needs, i.e. are designed barrier-free.

8.2.2. Walkability attributes

Over 30 attributes influencing walkability were identified based on a survey (see *Chapter 5*), literature reviews (see *Chapters 6 and 7*) and further research activities (cf. *Section 3.2.2*).

Personal reflection

The quantification of the number of walkability attributes recurs in several parts of this thesis (among others, in *Chapters 5* and *7*). While the number here is quantified as “over 30”, this number could easily be doubled or halved depending on how fine-grained the walkability attributes are defined. I have opted for a level of detail that is consistent with the extent of available spatial data to create a framework that provides detailed insights and is applicable at the same time. However, other researchers may have followed a different logic in quantifying the attributes influencing walkability, making a direct comparison of results difficult.

They are listed in *Figure 46* and clustered according to the hierarchy of walking needs.

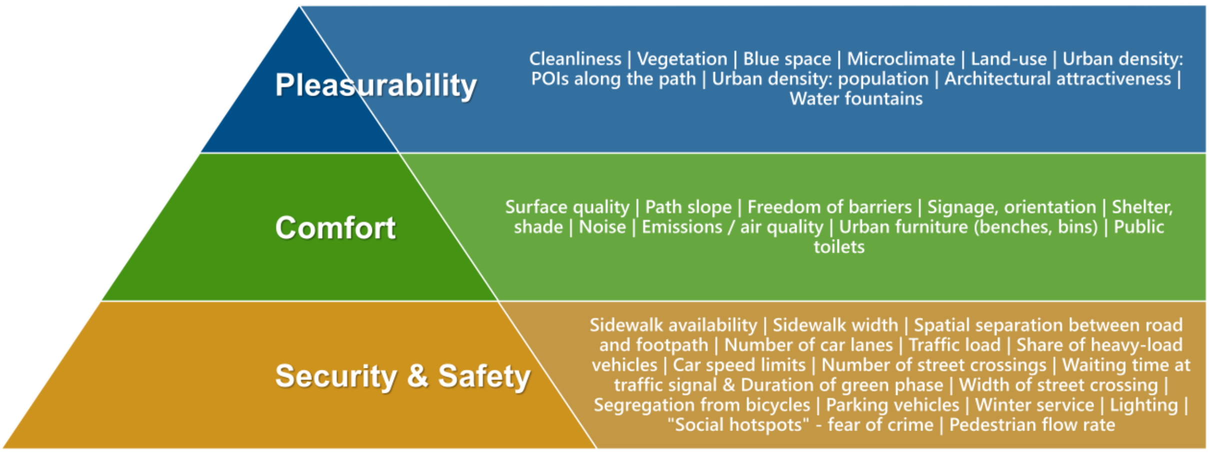


Figure 46: Identified walkability attributes, clustered according to the hierarchy of walking needs

The Access to Rail survey (see *Section 5.4*) showed that attributes related to comfort (e.g. freedom of barriers, noise, shelter and shade) and security and safety (e.g. lighting, pedestrian flow rate, sidewalk width, car speed, street crossings) were perceived as highly important in terms of pedestrian accessibility, which confirms that walkability attributes are an essential part of accessibility and matches with the pyramid of walking needs (cf. *Figure 2*). Attributes related to pleasurability (e.g. POIs along the path) were rated as less important but still have a noticeable effect. While these findings confirm the order of the pyramid of walking needs and the distinction between walkability and accessibility made in *Section 2.4.1*, this understanding was only developed after the publication of *Chapter 5*. Thus, in *Chapter 5* walkability was still seen as a synonym for pedestrian accessibility, as used by many other authors (cf. *Section 8.1.4*). However, making a clear distinction between these two terms seems advisable, as they are simply of different scales. Accessibility features should, therefore, not be treated in the same way as walkability attributes. Walkability evaluates how attractive paths are. Accessibility analyses whether there are any destinations available that can be reached via these paths. Only when accessibility is given does it make sense to analyse walkability for walking for transport, because if there are no destinations, trips will not be made on foot anyway. On the other hand, when analysing walking for leisure (e.g. as done by many health studies), accessibility is rather irrelevant.

The walkability attributes were clustered into groups, although it is challenging as most of the attributes affect several groups and the boundaries are fluid. Thus, various terms and categorisations were used in the course of this work (*Chapter 5*: Traffic Safety, Security, Comfort, Built Environment; *Chapter 6*: Protection from road traffic, Lighting & Subjective safety, Walking comfort, Liveliness & Walking Environment, Vegetation & Waters, Urban equipment; *Chapter 7*: Traffic safety and road influences, Security, Infrastructural quality and comfort, Environment and liveliness, Urban equipment). The categorisation was gradually refined with the growing understanding of the influencing attributes. Some attributes were previously assigned to other groups as they are assigned now in the synthesised results. For example, “sidewalk width” was seen as a *comfort* attribute in the beginning, but it is now considered within the *security & safety* category. In consequence, the importance of the categories changed with the reallocation of single attributes. The categorisation helps to understand the overall picture, but in the end, it is the influence of the individual attributes that count and not which group they are assigned to.

Personal reflection

During the work on this dissertation, my opinion on how detailed I want / can examine the attributes that influence perceived walking accessibility (per user groups) changed quite a bit. In the beginning, I was highly motivated to explore every single attribute in very detail and was confident that in the end, I can certainly say how much more important one attribute is over the other. In *Chapters 5*, *6* and *7*, I tried to do exactly this and, in my opinion, received results that looked plausible. However, the more I reflect on it, the less confidential I get in communicating my results as “the one correct answer”. As perceptions depend on so many factors (see whole *Chapter 8.2*), I see it more and more impossible to make a generalised statement, and thus leave my conclusions rather vague by mainly rating the importance of the walkability categories and not the single attributes. Based on this realisation, I have also removed this aim from the expected research outcomes in *Section 1.3* so as not to raise false expectations in the reader.

Walkability is always an interplay of several attributes. For example, the perception of traffic safety on a narrow sidewalk depends on the number and speed of the cars on the road. High traffic volumes and speeds increase the need for wide sidewalks and spatial separation between cars and pedestrians. However, a high traffic road is not inherently unwalkable. It can also be attractive to pedestrians if the remaining walkability attributes fit. For example, the Avenue des Champs-Élysées in Paris has a high traffic volume but appealing shops, beautiful building facades, trees and the spatial separation between the footpath and the road still make walking attractive (but without cars on the street it would perhaps be even more pleasant). As Chan, Schwanen, and Banister (2021) suggested, some attributes are negotiable and lower scores can be compensated by, and traded against, higher scores on others. However, the importance of the attributes varies. For highly important attributes, it may be difficult, if not impossible, to compensate.

8.2.3. User characteristics

Not only the relevant destinations, and thus the overall accessibility, but also the relevance of single walkability attributes varies greatly from person to person. Each person has other social, cultural and economic characteristics, such as age, gender, health status, lifestyle, nationality and income, which define their walking needs, capabilities and perceptions.

While every person is different, similarities in distinct population groups can be found. In the Access to Rails survey (see *Section 5.4*), age was shown to have the biggest influence on perceived walking accessibility, while only minor differences in regard to gender were found. The influence of age is in line with many studies confirming its relevance (e.g. Lättman, Friman, and Olsson 2016; M. Ryan et al. 2016; van der Vlugt, Curl, and Scheiner 2022; Curl 2018). Also Krauth (2021) found distinct needs for seniors and Wenkebach (2022) for teenagers. For gender, different studies have had opposing results, some finding gender differences (Chor et al. 2016; Suarez-Balcazar et al. 2020) and others not (Gebel et al. 2009; Arvidsson et al. 2012; van der Vlugt, Curl, and Scheiner 2022). Grundei (2021) found gender differences in perceived walkability at night caused by the feeling of insecurity, while during the day, there was no clear correlation between gender and perceived safety. Furthermore, freedom of barriers was a big topic in the Access to Rails survey, not only for people in wheelchairs but for everyone, as many people carry luggage on their way to the train station. This highlights that each person can have different user characteristics at different times, e.g. based on trip purpose or current health status.

The literature review on walking accessibility perceptions of different user groups (see *Section 7.3.2*) examined four users as examples of diversity in age, gender, and walking needs: children, seniors, women, and wheelchair users (the selection of these sample user groups is explained in *Section 8.3.3*). The results show that the importance of the walkability attributes varies a lot between user groups, confirming the hypothesis that one accessibility index alone cannot be sufficient to represent all individual needs, capabilities and preferences. While Jamei et al.'s review (2022) across all transport modes found that different studies obtained different clear results regarding the effects of user characteristics on perceived accessibility, clear tendencies were found in the literature review focussed on perceived walking accessibility. For example, for children, traffic safety is the most important. For wheelchair users, attributes such as freedom of barriers, sidewalk width and sidewalk surface, which are all part of the *comfort* category, were found to be the most important. Although comfort is at a high level in the pyramid of walking needs, for a wheelchair user, these factors have a direct impact on the feasibility (bottom of the pyramid). If a path is not barrier-free, a wheelchair user will not be able to use it. This highlights the importance of considering user characteristics as they can fundamentally alter the walking needs, in line with the capability approach (cf. *Section 2.5.1*) and indicates that perceived walking accessibility might be more sensitive to individual characteristics than perceived accessibility by other modes. The importance of the walkability attributes presented in *Figure 46* is, therefore, not set in stone but needs to be tailored to the needs of a particular user group. Thus, as also suggested by Chan, Schwanen, and Banister (2021), some attributes may be so important to certain people or in particular situations that they act as hard and non-negotiable constraints.

8.2.4. Geographical context

Furthermore, how walking accessibility is perceived depends on the geographical context. In different places around the world, the supply and demand of destinations varies. Urban structures, including walking infrastructure and environment, are different and people have different characteristics, mentality and habits. Thus, the literature review in *Chapter 7* showed that the importance of walkability attributes varies quite a lot, depending on the study context. Also the results from the Access to Rail survey (see *Section 5.4*) showed differences to previous studies conducted in India (Bivina, Gupta, and Parida 2019; Gupta, Bivina, and Parida 2022). Safety and security were ranked more important in the Indian studies than by the participants in Bavaria. Overall, differences are likely to be greater between places that are further apart. But there are also differences at the local level. The Access to Rail survey also found differences between the five cities in Bavaria based on city size. These findings support Boakye-Dankwa et al.'s (2019) suggestion that local contexts can influence how accessibility is perceived.

Personal reflection

Although my research involved activities in many different locations and global literature reviews were conducted, my on-site activities took place mainly in urban areas in Europe and Australia (see *Section 3.2*). Thus, my understanding of perceived walking accessibility is clearly shaped by these geographical contexts. While being aware that other global contexts present different barriers to walking, it is challenging to fully understand the influences on perceived accessibility without having experienced these local conditions first-hand. I realised this when I gave a lecture to a group of international students. When I presented my findings from studies on accessibility in Germany and started talking about comfort and pleasurability, some of them almost got upset with me. In many of their home countries, security and safety are such a big issue that they don't even think about comfort and pleasurability. They found it impertinent that I see micro-features such as the lack of benches as a problem, while they live in fear of being shot or robbed when they walk through their neighbourhood. This again shows that we in Europe are spoiled through quite high public security and safety levels. We thus have the luxury to complain about comfort and pleasurability and fine-tune the walking conditions to meet the needs on the top of the walking needs pyramid, while other parts of the world are currently facing the challenge of addressing the bottom needs. The same applies to rural places. While accessibility to daily needs is generally a given in urban settings, walking is often not an option in rural areas due to a lack of destinations within proximity.

8.2.5. Temporal changes

On top, how one and the same environment is perceived by one person can vary at different times. For example, based on weather (sunshine vs. rain), time of the day (day vs. night), trip purpose and mood. These temporal changes affect the walking needs of the people. For example, while street lighting is irrelevant during the day, it can become the most important walkability attribute at night. In the Access to Rail survey (see *Section 5.4*), “streets walkable in all weather conditions” was rated as one of the most important factors. Thus, ideally, the walking infrastructure and environment should be designed and maintained in a way to match the diverse needs of people that can easily vary based on the temporal conditions.

But not only walkability, also accessibility is influenced by temporal changes. Firstly, the opening hours of destinations have a direct impact. Secondly, different destinations have different relevance (e.g. outdoor activities when the sun is shining, indoor activities when it is raining). Thirdly, the path connectivity can vary as some paths are also limited to certain operating hours (e.g. some parks are closed at night) or are affected by natural events (e.g. paths located in floodplains become impassable after heavy rainfall).

8.2.6. Limitations

The results of the conducted and reviewed studies are dependent on the study context, the method, local conditions and the people participating. For example, the presence of benches and slopes did not play any role in the Access to Rail survey answers (see *Section 5.4*) and could thus be assumed as unimportant. In contrast, in Krauth’s (2021) study, which specifically asked seniors about their improvement wishes on the walking infrastructure, more benches were mentioned the most often. Regarding the slope, it has to be considered that the five study areas were all topographically flat. In hilly areas, the slope is, in fact, perceived as a barrier (McGinn et al. 2007; Sun et al. 2015). This highlights that depending on the questions we ask, the study areas we choose, the participants we pick and the temporal conditions that are given, results can highly differ. This contextual bias is hard to eliminate. Ideally, a neutral test setting where all influencing factors can be changed and assessed individually would be needed. Or, in the real world, a multitude of diverse studies is needed to obtain a comprehensive picture. Although different research activities were conducted within this dissertation, and a contribution to analyse and better understand the influencing attributes of perceived walking accessibility is achieved, it cannot be considered conclusive.

Only four sample user groups and their walkability needs were analysed in detail in the literature review on walking accessibility perceptions of different user groups. Although they were selected to represent different needs, the understanding of user-specific needs is far from complete. There is a need to analyse more user groups and to experiment with other groupings, e.g. based on trip purpose. Another limitation is that this research focused on urban areas. Although it is assumed that the overall findings are transferable to other locations, further studies in other global contexts may reveal additional insights. Furthermore, influencing factors on the destination side that might have an impact on perceived walking accessibility have only been analysed to a limited extent (see *Chapters 4* and *5*), with *Chapter 5* solely focusing on railway stations. However, different destination characteristics (e.g. opening hours, store size) may influence the destination attractiveness and different types of destinations may create different walking needs (e.g. on the way home from the supermarket, a person may need more space and be less willing to walk long distances because of carrying shopping bags; or on the way to work, people may have a specific preference for sealed and clean walking surfaces to avoid arriving with dirty shoes). Due to the large number of factors influencing perceived walkability and the myriad possible combinations of destination characteristics, user characteristics and resulting walkability needs, geographical features and temporal conditions, perceived walking accessibility remains a complex issue with many nuances that should be explored further.

8.3. RQ 3: Measure development

How can the variety of perceptions be represented in feasible, calculated accessibility measures?

One of the biggest challenges is probably that perceived walking accessibility cannot simply be measured but only stated by the people. Thereby, the factors at the bottom of the walking needs pyramid tend to be more "objectively" measurable, while factors more at the top of the pyramid tend to be more "perceived". In order to include the perceived factors, imputed perceptions seem to be an appropriate approach (see *Section 8.1.3*). Thus, a walking accessibility measure has been developed that "objectively" calculates accessibility (available opportunities and network connectivity), and for the more "perceived" walkability attributes the importance for different user groups is identified through a literature review and translated into a weighting schema.

In *Chapter 4*, the ideal requirements for future accessibility measures were identified (see also *Section 8.1*). These were taken as the basis for the measure development. A walking accessibility measure, PAW, that focuses on modelling the effects of the individual component on the transport infrastructure has been developed (*Section 8.3.1*). A key part of PAW is a walkability measure, which represents the security and safety, comfort and pleasurability of the walking path network and has been incorporated into the generalised cost statement of the accessibility formula by working with perceived travel time (*Section 8.3.2*). To be able to represent different user needs, capabilities and preferences, the measure can be tailored to different user groups. In this thesis, four sample user groups were examined (*Section 8.3.3*). The accuracy of the measure is highly dependent on the availability of local data. In addition, there is always a trade-off between accuracy and simplicity (*Section 8.3.4*). The practical relevance of the developed measure is discussed in *Section 8.3.5*. In *Section 8.3.6*, the limitations are presented.

8.3.1. Accessibility

Walking accessibility has four components, but only two – land-use and transport – can be addressed through planning. The other two – individual and temporal – are more or less given by the diversity of people, times of day, seasons and weather conditions (only a few characteristics, such as opening hours, can be influenced by planning or policies). The land-use and transport components must, therefore, be designed by planners to meet the different individual and temporal needs. To support them in this, the individual and temporal components should be made visible by including them in accessibility measures. This thesis focuses on the impact of the individual component on the transport infrastructure – and partly on the land-use component by considering the attractiveness of the walking environment. The other impacts of the land-use component, such as demand and supply, are mainly excluded from this work. Thus, the unequal value of destinations (represented through “k” in *Equation (3)*) was neglected. The same applies to the impacts of the time (represented through “t” in *Equation (3)*).

Following the recommendations from *Section 8.1,* the resulting measure PAW uses the pedestrian network with all its micro-features as transport component. On the individual component, distinct population groups are taken into account. Their distinct needs, capabilities and preferences regarding the walking infrastructure and environment are modelled by assessing if the transport and land-use components meet their requirements according to the capability approach (cf. *Section 2.5.1*). Thereby, perceived time is used as impedance factor, as also done by Erath et al. (2017), Boakye-Dankwa et al. (2019) and Gaglione, Cottrill, and Gargiulo (2021). This represents the fact that an attractive route is perceived as shorter than an unattractive one. Working with time also allows the incorporation of different walking speeds for different user groups in the generalised cost formula. While usually simple generalised cost formulas are used in contour-based walking accessibility measures (see *Equation (8)*), further elements were added to this formula within this work to incorporate walkability attributes and user needs (see *Equation (9)*).

Overall, the resulting measure PAW is a calculated accessibility measure that works with imputed perceptions. Imputed perceptions allow the results of perceptual studies to be applied to a larger area using spatial data, thus combining the advantages of perceived and calculated approaches. Within this work (see *Sections 4.4*, *7.4* and *8.1.3*), the assumption arose that imputed perceptions are the key to reducing the mismatch between calculated and perceived accessibility, as therewith the user perceptions can be taken into account and, thus, more realistic accessibility analyses conducted.

Personal reflection

The methodological approach of imputed perceptions has occasionally been criticised. Since the definition of perception is "how something is regarded, understood, experienced or interpreted" (see *Definitions*), it implies that it can only be captured by humans and not by machines. It would follow that it is essentially impossible to derive it by computation – which, in fact, does not happen; rather, perceptions from smaller areas are ascribed to larger areas. However, I agree that the most realistic walking accessibility results could be received by asking all persons about their perception of it. But this is not feasible. Perception studies are applicable for small study areas, but if the goal is to improve walking conditions on a big scale, easily transferable measures are needed. These characteristics (unfortunately) only apply to calculated measures, not to perceived measures. Therefore, an approach is needed to include perceptions in the calculations by making them quantifiable. This may be a bit contradictory, but it seems to be the easiest way for walking accessibility measures to approximate realistic results for large study areas. Working with imputed perceptions may not do justice to every single person, but it is at least a vast improvement over conventional accessibility measures.

8.3.2. Walkability

Working with imputed perceptions allows to assign different levels of attractiveness and thus impedances to paths, depending on their walkability attributes. In *Chapter 6*, a first walkability measure, WALKIE, was developed and then refined in the course of the PAW development (see *Chapter 7*). This walkability measure represents the top three elements of the walking needs pyramid (security and safety, comfort and pleasurability) and combines them in a multi-criteria analysis. The street scale is chosen as an analysis unit. To be able to represent the sometimes quickly changing environment, the paths are divided into segments of max. 100m length.

WALKIE was first developed for a study area in Munich and then applied to Freiburg and Augsburg. While in total over 30 walkability attributes were identified, it was not possible to include all of them due to limited data availability. Based on the local data availability, the list of considered attributes was adjusted. As a result, 18 walkability attributes were considered in the final WALKIE measure in Munich and 20 each in Freiburg and Augsburg. Compared to other studies (such as Jonietz and Timpf 2012; Anciaes, Nascimento, and Silva 2015; D'Orso and Migliore 2018; Erath et al. 2017), this is an improvement in terms of the number of attributes considered. Ideally, however, further walkability attributes should be included in the future if data availability allows it. Although Blečić, Congiu, et al. (2020) stated that there is no consensus on an exhaustive set of attributes to be considered (cf. *Section 2.4.3*), it seems logical that the inclusion of the most relevant attributes is inevitable and, in general, the more attributes included, the more accurate the results can be.

As not all walkability attributes are equally important, each is given a weight that has been calibrated through surveys and behavioural studies using the AHP. This process is in line with

Personal reflection

Although I stated in *Section 8.2.2* that I consider it virtually impossible to make a generalised statement about the exact importance of each individual walkability attribute, this is of course necessary in order to assign different weights to various walkability attributes, so that these can be integrated into in a walkability or accessibility measure. Vague statements such as "x is more important than y" are therefore not sufficient. Instead, concrete numbers are needed. They are an important methodological component but should not be seen as more than that.

the workflow suggested by Venerandi et al. (2024) (cf. *Section 2.4.3*). To smooth out bias from certain studies, a plethora of existing study results were combined (see *Section 7.3.2*). Although there are certain deviations between the minimum and maximum values of the various study results for the individual walkability attributes, clear trends in their importance can be recognised, which suggests that the results are a representative average of the users' perceptions. The values of the walkability attributes are summarised to a total walkability index by using an additive approach, where the walkability score builds the sum of all weighted attribute scores (see *Equation (5)*). While this approach is rather simple and thus easy to understand, in some regards it might be too simplified. It is not able to represent the suggestion by Chan, Schwanen, and Banister (2021) that some attributes may be so important to certain people that they act as hard and non-negotiable constraints. In an earlier measure approach (see Jehle 2020), a decision tree with hard constraints, as suggested by Chan, Schwanen, and Banister (2021), was used. However, the results of it only distinguished between "usable" and "non-usable" paths, without giving detailed insights into its walkability. In order to be able to show the full range of walking perceptions, but at the same time keep it simple and understandable, the additive approach was chosen for the final WALKIE measure. However, a mixture of both approaches might deliver the most realistic results.

8.3.3. User groups

To represent the whole *"variety of perceptions"*, ideally the perceptions of each single person should be analysed. However, this is not practicable and although every person is different, similarities in distinct population groups are found. Furthermore, planning and policymaking are usually for the average of the whole population or a certain population group. Thus, as argued in *Sections 4.4* and *8.1.1*, it is sufficient and adequate to focus on a selection of user groups that represent the various needs of pedestrians. For the measure development of PAW, four sample user groups were selected: children, seniors, women, and wheelchair users. The selection of the user groups was influenced by the findings from previous perception studies (see *Section 8.2.3*) and by the choice of existing user-specific measures, which mainly distinguished between older adults, wheelchair users and children (see *Section 8.1.1*). Seniors and children are interesting, as both represent different age groups – a characteristic that has been identified to have a large impact on perceived accessibility. Furthermore, wheelchair users clearly have specific requirements. These three user groups focus on barrier-free infrastructure, safety and comfort. When looking at the pyramid of walking needs (cf. *Figure 2*), it becomes clear that security needs are neglected in the current user group choices. Studies (e.g. Bivina and Parida 2024; Sethi and Vélez-Duque 2021) have shown that these security needs are especially important for women. Although traditional gender roles are outdated and boundaries, in reality, are fluent, women were chosen as the fourth user group

Personal reflection

When discussing my work with researchers and practitioners, the user group "women" was often criticised as it sticks too much to traditional gender roles. Interestingly, almost all persons that raised this critique were men. Women seemed to be okay with the selection of user groups and being classified as the gender with higher security needs. While in our current times, it indeed would be more appropriate to be progressive in this regard, gender is still one of the main socio-demographic characteristics that researchers use when conducting surveys and behavioural studies. Thus, the insights from literature mainly distinguished between "men" and "women", with several of them finding that women's needs differ from men's needs. While I am aware that also men have security needs and people not solely can be clustered in "men" and "women", I would today still make the same decision when defining the sample user groups, as "women" is an easily understandable user group that everyone can identify with. But in a few years' time, when more behavioural studies with a more up-to-date definition of gender are available, this may be worth updating.

to obtain four sample groups with a high variety, representing the different needs of the population. However, these are only sample groups to demonstrate the adaptability of the measure. Depending on the case study and application of the measure, own user groups can be defined.

For each of these sample user groups, their average walking speeds and weighting factors for the walkability attributes were defined, following a similar approach that Golan et al. (2019) and Moura, Cambra, and Gonçalves (2017) have used. Those were derived through a global literature review (see *Section 8.2.3*). Per user group, the results from ten different studies were combined. Therewith, a large sample size of diverse people from different global contexts was obtained. These global results were applied to Munich and Augsburg, which is not methodologically ideal but fulfils the purpose of testing the developed measure.

While conventional accessibility measures treat all persons as the same, the here-developed PAW allows the adjustment of the walkability perceptions and walking speeds based on the user group. The capability approach (cf. *Section 2.5.1*) was conceptualised to assess whether the internal factors of the user groups match with the external factors of the infrastructure and land use. Blečić et al. (2015), Fancello, Congiu, and Tsoukiàs (2020) and Reyer et al. (2014) have used similar approaches for walkability measures, however, this research went one step further and linked this to the perceived walking accessibility of different user groups. PAW is based on a similar logic to Amaya et al.'s (2022) and Gaglione, Cottrill, and Gargiulo's (2021) approach, but is more advanced in that it considers a greater number of walkability attributes and includes additional user groups. Overall, the call for future research to more comprehensively identify and include the walkability attributes (Golan et al. 2019; Chan, Schwanen, and Banister 2021; Amaya et al. 2022; Gaglione, Cottrill, and Gargiulo 2021) and apply them to additional user groups (Chan, Schwanen, and Banister 2021; Fancello, Congiu, and Tsoukiàs 2020) was realised.

8.3.4. Trade-off between accuracy and simplicity

To achieve a *"feasible"* accessibility measure, a trade-off between accuracy and simplicity is inevitable. With the large number of attributes that influence perceived walking accessibility, the measure automatically becomes somewhat complex. On the one hand, this complexity is necessary to obtain realistic results. On the other hand, keeping it simple and understandable is crucial for its application in planning practice. Therefore, it is necessary to find the right balance between "scientific rigor (soundness) and their practical relevance (plainness)" (Papa et al. 2015, p. 73). This applies to several aspects of the measure. First, the individual component. In *Chapter 6*, a walkability index for a "standard" pedestrian was developed. However, while one common index is the easiest to communicate, something like a "standard" pedestrian actually does not exist; rather, it is an average of multiple diverse individual needs, perceptions and capabilities. As *Simpson's paradox* says, when we aggregate data, we also lose specificity. Thus, using representative sample user groups with distinctive needs was seen as a reasonable compromise in the final measure PAW. Second, for the walkability index, it was decided to choose an additive approach without hard constraints as a trade-off. The focus was set on the definition of different weighting factors per user group to represent the varying relevance of the walkability attributes, while the attribute scores were assumed to be the same for all persons. Third, PAW was developed as a contour-based measure, as they are acknowledged to be easy to understand (Geurs and van Eck 2001; Albacete 2016), which contributes to their widespread adoption by practitioners (D. O'Sullivan, Morrison, and Shearer 2000; Papa et al. 2015). If the here presented measure is considered valuable and worth enhancing, further complexity can be added in future.

Similarly, for the data needed to feed the measure, a trade-off between accuracy and complexity is required (see *Sections 4.5 and 7.4.4*). For each case study application, the measure needs to be adapted to the locally available data sets. Ideally, the pedestrian network with all its micro-features and walkability attributes exists as spatial data and a local survey of user group perceptions of walking accessibility is available. However, this is usually not the case. It is therefore necessary to gauge which datasets are indispensable and should therefore be collected, which can be compensated by proxies and which can be neglected. *Chapter 7* presents some strategies for dealing with the unavailability of some datasets. For example, if no local perception study is available, the AHP method can be used to derive average weighting factors based on studies from other areas. Overall, however, it is important to remember that a model can only be as good as its input data.

8.3.5. Practical relevance

Walking accessibility measures can help to improve the overall walking conditions (cf. *Sections 1.3 and 2.3.2*) and thus increase the walking shares in a city or neighbourhood (cf. *Section 1.2*). In order to serve as a useful decision support tool, measures should be able to adequately model reality. However, it has been found that conventional calculated accessibility measures are not able to represent accessibility as it is perceived by people. It seems like perceived walking accessibility is more complex in terms of influencing factors as well as more sensitive to individual characteristics than perceived accessibility by other modes (see *Sections 4.1.1 and 8.2*), resulting in a need for a large amount of data. While a decade ago, data availability was the biggest institutional barrier blocking the use of accessibility instruments (Papa et al. 2015), a high increase in data availability has been observed since then. Thus, one of the biggest barriers has been lowered. Furthermore, regarding user perceptions, the methodological approach of imputing perceptions seems to be promising to reduce this mismatch between calculated and perceived measures and generate more realistic results.

The developed measure PAW was implemented in the planning tool GOAT for the example of Munich. Intermediate versions were tested and discussed with local practitioners in Freiburg (see *Section 6.5*) and Augsburg. They found the results insightful and saw potential in this measure. Although the data requirements for PAW are high, the barriers to using the measure are assumed to decrease further with increasing global data availability, increasing willingness to invest in data collection and open data platforms, and increasing use of GIS. Based on the overall observed increase in walking accessibility studies, it can be assumed that there is a general interest in novel measures in planning practice and research. It seems like the time for walking accessibility measures has come (see *Section 8.1*).

PAW can help planners to design cities with good walking conditions for all. The results present isochrones that show the perceived walking accessibility for specific user groups. In the sample calculation (see *Chapter 7*), it was assessed how many people can access certain POIs. Similarly, other starting points and destination potentials can be picked. PAW can thereby assist planners in ensuring that important destinations, such as supermarkets or public transport stops, are accessible to all user groups. Likewise, for POIs that are of user-specific interest, e.g. schools, PAW for these specific user groups can be performed. Therewith, shortcomings in the perceived walking accessibility can be identified. Those can be of different nature with regard to the different levels of the pyramid of walking needs (cf. *Figure 4*), namely: lack of destinations in direct proximity, low connectivity of the pedestrian network or low walkability that makes walking unattractive and increases the perceived walking time, with many different factors that can cause this. Some of these shortcomings are easier to solve than others. Overall, issues related to the transport infrastructure can be addressed easier than issues related to land use. Thus, by assessing the details of the PAW analysis, the reasons for the accessibility shortcomings can be identified and appropriate actions defined to improve the situation.

Furthermore, the findings of this work can help other researchers and practitioners to gain a deeper understanding of walking accessibility in general as well as for specific user groups, its influencing factors and how to measure it, potentially providing new insights that will also help improve existing accessibility measures and contribute to the overall rise of accessibility-based planning (Pot, van Wee, and Tillema 2021).

8.3.6. Limitations

As the aim was to develop a walking accessibility measure that includes walkability attributes and user needs, the focus was on the individual component and its interplay with the transport component (cf. *Section 3.1*). The interplay between the individual and the land-use component (e.g. which destinations are important for which user group) was mainly neglected, and only the attractiveness of the walking environment was considered (see *Section 8.3.1*). Also, the influencing factors of the temporal component, such as light conditions, weather and opening hours (see *Section 8.2.5*), were excluded from this new measure development. In order to achieve a feasible measure, a trade-off between accuracy and simplicity (see *Section 8.3.4*) was inevitable. Most of the decisions were made in favour of simplicity. Although, ideally, all four accessibility components should be considered in an accessibility measure (see *Section 8.1.1*), this was not possible to achieve in this thesis (cf. *Figure 5*). Thus, there is a high potential to increase the complexity of the measure and thereby increase its accuracy.

The developed measure follows the hierarchy of the walking needs pyramid (cf. *Figure 2*), where accessibility builds the basis. As accessibility is on another spatial scale than walkability (see *Section 8.2.2*), these two parts are evaluated based on different methodologies (see *Equation (5)* and *(6)*). The walkability attributes of the three top levels of the pyramid (*security and safety*, *comfort* and *pleasurability*) are thereby handled the same, only receiving different weights. However, it could be argued that also each of the top three levels should be evaluated in its own way.

Furthermore, some of the walkability attributes had to be excluded from the measure application, as no data was available (see *Section 8.3.2*). Ideally, if the data allows it, all walkability attributes should be included. However, there are some attributes, such as architectural attractiveness, which might not be possible to capture "objectively" through spatial data at all (Shields et al. 2021). Thus, even when working with imputed perceptions, it may not be possible to model the perceived accessibility to its full extent. To do so, a combination of calculated and perceived measures might be needed, which e.g. includes real user statements for those attributes.

Four user groups were examined to represent the diverse user needs. However, these are only examples. Based on the planning questions, weighting factors for further user groups should be determined. Furthermore, the presented weighting factors for the four sample user groups were derived through a global review. Therefore, when applied to a specific case study, the weighting factors should ideally be adapted to the local context by using local perception data.

The developed measure was implemented, applied and juxtaposed with conventional time-based accessibility measures. Although clear differences between PAW and conventional measure results can be seen, no real tests have been carried out to prove that PAW is actually advanced. The PAW results have not been compared with perceived studies for the same area. Therefore, no statement can be made about its ability to model the perceived accessibility more realistic. Only by comparing the characteristics of PAW with the recommended practice (see *Section 4.4*) can it be stated that the recommended practice has been met for the transport component, the individual component, the impedance calculation and the type of measure. However, this is only on paper and has not been proven in practice.

Interestingly, Handy and Niemeier's (1997, p. 1176) statement still holds true: "Although it is easy to say that a measure of accessibility must be developed, it is much harder to say exactly how to do this." PAW is one way of addressing the recommended practice, but it is certainly not the only one. It is an approach to making the theoretical recommendations applicable to planning practice, but might not yet be the perfect solution.

9. Conclusions

This research gained a deeper understanding of how walking accessibility measures are constructed and which attributes have an impact on perceived walking accessibility. Based on the findings, a new accessibility measure, PAW, that includes walkability attributes and user needs was developed. This chapter concludes how the mismatch between perceived and calculated accessibility was addressed (*Section 9.1*), shows further research needs and development paths (*Section 9.2*), and gives an outlook on how this can contribute to a more sustainable transport sector and the creation of liveable cities (*Section 9.3*).

9.1. Addressing the mismatch

The mismatch between perceived and calculated accessibility measures was confirmed in this research (see *Section 8.1.3*), highlighting the inability of conventional calculated accessibility measures to capture accessibility as it is perceived by people. It was found that conventional calculated accessibility measures mainly use distance or walking time as impedance, that they usually do not represent the walking network with all its micro-elements and mainly neglect people's needs, capabilities and preferences (see *Section 8.1*). Perceived accessibility was found to be influenced by many factors (see *Section 8.2*): accessibility (proximity to destinations, network connectivity), walkability (security and safety, comfort, pleasurability), user characteristics (age, health status, trip purpose, etc.), geographical context (urban structures, mentality, etc.) and temporal changes (weather conditions, time of day, etc.). The majority of these factors seem to be more complex than for other modes and are neglected in conventional calculated accessibility measures, which generates the mismatch. However, calculated measures have the advantage of being easily transferable to larger areas. Therefore, recommendations for future calculated accessibility measures have been made and implemented through the development of PAW (see *Section 8.3*). PAW combines the advantages of both approaches by working with imputed perceptions and using perceived travel times, as well as incorporating walkability attributes and providing different settings for different user groups. The measure evaluates, based on the capability approach, whether the internal factors of the user groups match the external factors of the infrastructure and environment.

With PAW, an approach was developed to reduce the mismatch and thus produce more realistic analysis results. It was found that conventional accessibility measures often overestimate, but sometimes also underestimate, accessibility compared to PAW. However, whether PAW is a more realistic representation of walking accessibility than existing methods remains to be assessed. The mismatch has certainly not been completely eliminated, as not all influencing factors could be included in the measure within this work, but it has presumably been reduced. In addition, this research has contributed to the overall understanding of pedestrian accessibility and created further awareness that conventional calculated accessibility measures are only capable of representing the perceived walkability to a limited extent.

9.2. Further research needs and development paths

This research has introduced a new measure of walking accessibility and has contributed to resolving the mismatch between perceived and calculated accessibility. However, there are many different directions in which the developed measure PAW can be further developed, as well as additional research questions that arise from it. This section summarises potential research agendas.

Conceptualising the definition of walkability: The lack of a generally accepted definition (see *Section 2.4.1* and *8.1.4*) often leads to misunderstandings and misinterpretations in research and practice. Further efforts are needed to conceptualise walkability and create a common understanding of it, highlighting the interdependencies with accessibility while drawing clear boundaries between these two terms.

Exploring the influencing attributes further: Although findings on the importance of different attributes on perceived walking accessibility were presented in *Section 8.2*, further work is needed to explore each individual attribute fully. However, as perceived accessibility depends not only on the given infrastructure and walking environment but also on person, location and time, it is always an interplay of different factors, and it may be impossible to evaluate them separately. A neutral test setting in which all parameters can be controlled individually would be necessary for this.

Adding non-negotiable factors: For calculating the walkability index in PAW, an additive approach without hard constraints was chosen (see *Section 8.3.2* and *8.3.4*). This is simple but neglects the fact that some attributes, such as freedom of barriers for wheelchair users, serve as limiting constraints. Thus, there is potential to further refine the measure by defining negotiable and non-negotiable factors.

Evaluating PAW: The developed measure PAW has been implemented and tested for different case studies. Although the results differ significantly from conventional accessibility measures, it has not yet been proven that PAW actually represents walking accessibility more realistically (see *Section 8.3.6*). Ideally, structured tests should be conducted to compare PAW results with conventional calculated accessibility measures and perceived accessibility studies.

Considering the temporal component: Temporal changes, such as weather, light conditions and opening hours, were found to be important factors influencing perceived accessibility (see *Section 8.2.5*). However, they have been neglected in the PAW measure development and were also found to be mostly neglected in existing accessibility measures (see *Section 8.1.1*). Further research should thus focus on this forgotten but important component.

Applying PAW to further user groups: PAW was applied for four sample groups (see *Section 8.3.3*). However, there is much more potential, and it is inevitable that the method will need to be extended to additional user groups, such as teenagers or visually impaired people, to fully represent all the diverse needs of people. In addition, user groups based on other characteristics, such as the purpose of the trip, may also be useful.

Providing individual routing: While the aim of this work was to provide more realistic walking accessibility analyses for decision makers (see *Section 8.3.3*), the methodological approach of using imputed perceptions and perceived time to weight the attractiveness of paths can also be used to develop routing algorithms that can show individuals the best route to a particular destination based on their needs, capabilities and preferences. This can be done either by using generalised user groups or by providing fully customisable routing profiles where each person can define their preferences.

Adapting PAW to local contexts: For the PAW calibration, perception data from all over the world were used as input data due to the lack of survey results from the specific study area (see *Section 8.3.4*). However, when using PAW for a case study, the weighting schema should ideally be adapted to the local context and calibrated with local perception studies.

Representing the land-use component more realistically: The influences of the land-use component on perceived walking accessibility were only considered through the attractiveness of the walking environment and the destination potential, using only simple population numbers in the example application (see *Section 8.3.1*). To fully represent the land-use component, further focus on destination potential is needed, e.g. by analysing how many children live within reach, or by assessing which POIs are relevant to which user group and how attractive they are based on their characteristics (e.g. service frequency, opening hours, sales area).

Exploring further approaches to include perceptions in calculated accessibility: Imputed perceptions and perceived time were chosen as methodological approaches to represent user group specific perceptions in calculated accessibility measures (see *Section 8.3.1*). But this is certainly not the only valid approach. Other ways of including perceptions in calculated accessibility measures, such as working with actual behavioural data, should be explored further.

Converting into gravity-based measure: PAW was developed as a contour-based measure, which creates easily understandable results and is well suited for point-based analyses (see *Section 8.3.4*). However, for area-wide analyses, it might be helpful to convert PAW into a gravity-based measure. Thereby, the influence of the individual component on destination needs and attractiveness, as well as individual walking distance thresholds and decay functions, should be considered.

Providing decision support: PAW was implemented in the planning instrument GOAT where the resulting walkability index and isochrones were able to visualise. Low scores can thereby have many causes, ranging from macro issues such as lack of destinations to micro issues such as uneven walking surfaces (see *Section 8.3.5*). Micro issues are usually easier to address than macro issues. It may, therefore, be useful for practitioners not only to visualise the walkability index and isochrones but also to highlight shortcomings that can be easily addressed. Furthermore, a scenario function could be provided to assess the impact of different planning actions, e.g. increasing pavement width, on walking accessibility.

Exploring novel data collection methods: While this work has only used AI to detect objects from street-level images (see *Section 6.3.3*), the possibilities of this technology are growing rapidly. Blečić, Cecchini, and Trunfio (2018) have already experimented with automated assessments of perceived walkability from street-view images using machine learning. This technique could have great potential to simplify data collection and model calibration in the future.

9.3. Outlook

Due to the long-standing prioritisation of motor vehicles, the undersupply of decision-support tools that adequately model walking accessibility, and the lack of fine-scale data, walking has been neglected by planning practice for a long time. Thus, a high potential for improving walking conditions can be found in many cities. The walking accessibility measure PAW, as well as the overall findings on the influencing attributes of walking accessibility from this research, can help to create more awareness of walking needs and apply these findings to planning practice.

The developed measure PAW can be customised to any user group and transferred to study areas worldwide. It is a versatile method that can be adjusted to different input parameters and applied in various contexts. Although a large amount of data is required for the application of PAW in a new study area, it is assumed that the increasing availability of data will open up new possibilities and also enable a gradual refinement of the method. By implementing PAW in accessibility instruments, PAW can help planners and decision makers around the globe to design cities with good walking conditions for all. It provides insights into how perceived accessibility varies for different user groups, opening up this perspective to the planners.

Based on the measure results of PAW, shortcomings in the perceived walking accessibility can be identified and appropriate actions defined to improve the situation. Good accessibility to important destinations, including attractive walking infrastructure and environment that matches people’s needs, is key to achieving a more walking-orientated behaviour of the population and increasing the walking shares. Depending on local conditions, different issues need to be addressed in planning. For example, in rural areas, securing walking accessibility to essential needs is usually the main objective. In urban areas with high accessibility, walkability, i.e. security and safety, comfort and pleasurability, are the next matters that have to be addressed. Thus, the walking needs should be fulfilled from bottom to top, considering different user groups. When the most vulnerable groups are taken as a benchmark, all pedestrians usually benefit from it.

As walking can not only be considered the most sustainable means of transport but is also an important enabler of public transport, ensuring good walking conditions contributes to the shift towards sustainable modes on many levels. In times of climate change with the urgent need to reduce CO_2 emissions in the transport sector, this is an inevitable step. Many planners and decision makers have already realised this and have made the aim of creating liveable cities the highest priority. With increasing data availability and ability of walking accessibility measures to generate realistic results, planners finally get what they need in order to make their aims reality. Therewith, cities that are inclusive, sustainable and liveable can be achieved.

Afterword

The first years of working on this dissertation took place during the COVID-19 pandemic. The restrictions on public life have definitely helped me to focus on my research; and conversely, this research has kept me busy in lockdown. However, because of the restrictions, many conferences were held virtually, travel plans had to be adjusted, face-to-face discussions were limited, and personal exchanges with other researchers came short. In short, COVID-19 was both a driver and a barrier in my research process. However, the pandemic also had an impact on a larger scale. It changed mobility habits and helped the population to rediscover walking – not only as a leisure activity but also as a “safe” (infection-free) means of transport. Today, in the summer of 2024, COVID-19 no longer directly impacts public life, but its indirect effects can still be seen in the form of redesigned public spaces, such as traffic-calmed areas or pop-up cycle lanes and parklets that have become permanent. So the pandemic has at least had the positive side-effect of making us rethink the distribution of public space and opened a window of opportunity for change. I hope this drive remains in planners’ and citizens’ minds, even now that life has returned to normal.

Declaration of generative AI and AI-assisted technologies in the writing process

The author of this dissertation used DeepL and Grammarly to improve the written texts. The content was reviewed after using these tools, and the author takes full responsibility for it.

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