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A five-component conceptual model of calculated and perceived accessibility: Literature review and research directions

Karst Geurs [a,*], Bert van Wee [b]

[a] Department of Civil Engineering and Management, Faculty of Engineering Technology, University of Twente, Drienerlolaan 5, 7522NB Enschede, the Netherlands
[b] Faculty of Technology, Policy and Management, Delft University of Technology, the Netherlands

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ABSTRACT

This paper presents an accessibility literature review and updates the accessibility definition and conceptual model of Geurs and van Wee (2004). The paper presents a five-component conceptual model for both calculated and perceived accessibility, which suggests that accessibility depends on the transport system, land use system, digital infrastructure and technologies, characteristics of people and their social interactions, and the temporal component, as well as numerous mutual interrelationships. The paper reviewed operationalisations of calculated and perceived accessibility, which measure accessibility in different ways and show different perspectives on accessibility. The addition of the digital component of accessibility is the first main extension of our conceptualisation of calculated and perceived accessibility. The literature review, however, shows that the direct and indirect impacts of digitalisation on calculated and perceived accessibility are understudied. Existing studies primarily focus on the impacts of teleworking and telehealth on calculated accessibility. The second main extension to the 2004 conceptual model is the addition of social interactions to the individual component of accessibility. The review shows that existing calculated and perceived accessibility studies, however, typically ignore social interactions within households and local communities, which can help to overcome accessibility barriers and influence perceptions of accessibility. The paper identifies several directions for future research, including the direct and indirect impacts of digitalization on calculated and perceived accessibility, as well as the further development of perceived accessibility and equity measures.

1. Introduction

The growing interest in accessibility in policy making and planning increases the need for a sound understanding of what accessibility is, which factors influence levels of accessibility for whom, and how to value levels of accessibility. Geurs and van Wee (2004) published a literature review paper on the accessibility evaluation of land use and transport strategies in the Journal of Transport Geography. That paper has become the second most cited accessibility paper after Walter Hansen's seminal paper ‘How Accessibility Shapes Land Use’ (Hansen, 1959)[1]. The development of the number of citations to the Geurs and van Wee, 2004 paper in the past 20 years also illustrates that accessibility is a rapidly growing field of research, i.e., over 83% of citations (listed in Scopus) were from papers published in the past 10 years (2016–2025), and 56% of citations were from papers published in the last five years (2020 or after).

Briefly summarized, the conceptual model for accessibility presented by Geurs and van Wee was based on four components (i.e., the transport, land use, individual, and temporal components), and several direct and indirect relationships between these components and between accessibility of opportunities and these components. This core conceptual model can be considered as very generic and robust and has been used as a basis in many accessibility studies. However, it has been over two decades since it was published.

This paper provides an update of that model, addressing three main limitations in the 2004 conceptual model. First, a major limitation is the lack of a digital component of accessibility. The 2004 paper focused on the factors explaining physical accessibility to spatially distributed activities and did not include the role of ICT and digitalisation in accessibility. The words ICT and digitalisation are not even mentioned in the paper. Although the 1990s can be seen as the starting point of the digital revolution (Lyons, 2014), the 2004 accessibility review paper was

* Corresponding author.
E-mail address: k.t.geurs@utwente.nl (K. Geurs).

[1] The paper from Geurs and van Wee (2004) has been cited 2412 times in Scopus, the paper from Hansen (1959) over 2994 times (February 26, 2026).

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written before the massive uptake of mobile digital technologies. There was hardly any attention paid to ICT and virtual accessibility in the accessibility literature until the mid-2000s. In the mid-2000s, digital technologies were launched that fundamentally changed people's opportunities to access people, goods, and services, including navigation, smartphone-based mobility services, voice and video over the internet (see for a discussion Bonin and Geurs, 2025); which also triggered accessibility studies to conceptualize how virtual space can be included in accessibility metrics (see Section 2.6). More recently, the COVID-19 pandemic has triggered a strong, global increase in the adoption of online activities substituting physical trips, and many studies show that the importance and the frequency of engaging in telework, teleconferencing, online learning (e-learning), telehealth, and online shopping (e-shopping) significantly increased during COVID-19 (e.g., Mouratidis and Papagiannakis, 2021). A second limitation is that the 2004 model departs from individuals, ignoring social interactions within households and local communities, which can help to overcome accessibility barriers and influence perceptions of accessibility. Third, since the 2004 review paper, a rapidly growing number of studies have examined perceived accessibility, i.e., the perception of how easily one can access their desired destinations using a (range of) specific mode(s) (Negm et al., 2025; Pot et al., 2021). Perceived accessibility can deviate from accessibility calculated from spatial and transport data (from now on, in this paper the term ‘calculated accessibility’ is used), e.g., due to differences in awareness of travel options, over- or underestimation of nearby activities, and measurement inaccuracies (e.g., Pot et al., 2021). For communication reasons, this paper does not integrate calculated and perceived accessibility in a single conceptual model, but presents a separate conceptual model for perceived accessibility, based on the components for calculated accessibility. We consider these three developments as the most important reasons to update the 2004 accessibility review paper.

This paper aims to present a revised conceptual model for the components of calculated and perceived accessibility and discuss operationalisations and gaps in the knowledge. The methodology used for this paper is a mixed one, consisting of various searches with different combinations of keywords in both Scopus and Web of Science, snowballing, and our knowledge of transport and accessibility literature. The paper is limited to passenger transport, ignoring goods transport, and departs from the perspective of persons and households (origins), not the destinations (e.g., employers, shops, services), but most of what is argued in this paper is also relevant for the perspective of destinations.

The remainder of this paper is structured as follows. Section 2 briefly presents a five-component conceptual model of calculated accessibility, describes possible interactions between the added and revised components (digital component, individual and social component) to the other accessibility components, and discusses operationalisations. Section 3 presents a five-component conceptual model of perceived accessibility and reviews operationalisations of perceived accessibility. Section 4 discusses the practical implications of our conceptual model for accessibility analysis. Section 5 presents the conclusions and outlines directions for further research.

2. A five-component conceptual model for calculated accessibility

2.1. Definition and components of accessibility

Geurs and van Wee (2004, p. 128) paper 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)”. In a later publication, the definition was slightly revised by distinguishing between the perspective of persons and locations of activities and added “at various times of the day” to include the role of the temporal component of accessibility explicitly (Geurs and van Wee, 2004, p. 208). Adding a digital component implies also the need to revisit the 2004 definition of accessibility. Focusing on the perspective of persons, accessibility can be defined as *the extent to which land-use, transport, and digital communication systems enable (groups of) individuals to participate in activities and reach destinations online and/or through a (combination of) transport mode(s), at various times of the day*. This new definition can be used in studies focusing on accessibility conceptualisations, analysis, and modelling of opportunities in hybrid physical-virtual space. Obviously, the frequently used definition from the 2004 paper is still useful in accessibility studies focusing only on physical accessibility. Note that this definition does not explicitly exclude activities that do not have a functional physical equivalent, such as online gaming, to avoid adding more complexity to the definition. These activities or opportunities, however, are typically not within the domain of interest of accessibility studies and land use and transport policy and planning.

Fig. 1 presents the updated accessibility model. To distinguish from perceived accessibility, “accessibility to opportunities” is relabelled as calculated accessibility. Briefly summarized, the model implies that accessibility levels depend on five components and several direct and indirect relationships between these components and between calculated accessibility and these components. This paper summarises the components and their relationships here and refers to the 2004 review paper for a detailed explanation. The focus is on the components that have been added or revised, and their interactions with the other components. Because adding and integrating the digital component to the 2004 model is the most important proposed change, this component is discussed extensively below. The five components of accessibility are summarized as follows:

1. The **land use component** reflects “the land use system and consisting of (a) the amount, quality and spatial distribution opportunities supplied at each destination (jobs, shops, health, social and recreational facilities, etc.), (b) the demand for these opportunities at origin locations (e.g., where inhabitants live), and (c) the confrontation of supply and demand for opportunities with restricted capacity such as job and school vacancies and hospital beds” (Geurs and van Wee, 2004, p. 128).
2. The **transport component** reflects “the transport system, expressed as the disutility for an individual to cover the physical distance between an origin and a destination using a specific transport mode, included are the amount of time (travel, waiting and parking), costs (fixed and variable) and effort (including reliability, level of comfort, accident risk, etc.)” (Geurs and van Wee, 2004, p. 128).
3. The temporal component reflects “the temporal constraints, i.e. the availability of opportunities at different times of the day, and the time available for individuals to participate in certain activities (e.g. work, recreation)” (Geurs and van Wee, 2004, p. 128).
4. The **individual and social component** first reflects “the needs (depending on age, income, educational level, household situation, etc.), abilities (depending on people's physical condition, availability of travel modes, etc.) and opportunities (depending on people's income, travel budget, educational level, etc.) of individuals” (Geurs and van Wee, 2004 p. 128). Second, it reflects how interactions within households, families, and broader social networks in local communities affect individual needs, abilities, and opportunities to participate in activities and to travel.
5. The **digital component** reflects digital infrastructures and technologies (including personal computers, mobile devices, and infrastructure-related information provision technologies) and digital services, allowing people remote access to activities, goods, and services, reducing the need for physical travel and/or improving the efficiency of travel, or enriching travel experiences.

Fig. 1 illustrates that the five components have a direct influence on calculated accessibility but also an indirect one through interactions between the components. The role of accessibility in land-use and

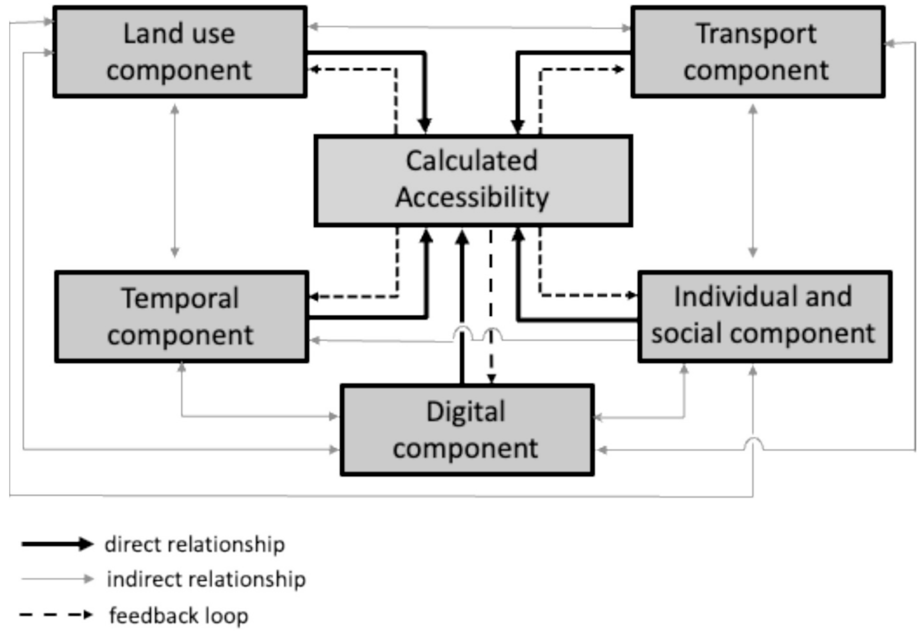

Fig. 1. Five-component conceptual model of calculated accessibility.

transport interactions is well-known and has already been studied for decades. Hansen (1959) already demonstrated that locations in Washington, DC, with good accessibility had a higher chance of being developed, and at a higher density, than remote locations. The relationship between transport and land use, via the accessibility feedback loop, was included in the 2004 conceptual model, but did not include an arrow from transport to land use. Here, a bidirectional relationship is added between land use and transport to reflect institutional and regulatory contexts that drive factors such as culture and values, policies, laws, and practices (Rietveld and Stough, 2006; de Abreu e Silva et al., 2023), which influence the functioning of the transport system and potentially influence land-use choices. These factors are typically treated as contextual factors in land-use/transport interaction and accessibility studies, which can influence transport systems in a study area, region, or country, rather than relative differences in transport impedances and accessibility levels within a case study area.

In the following sections, the additions to the conceptual model are described, compared to the 2004 accessibility model. Section 2.2 describes the interactions of the individual and social component of accessibility with the other components. The interactions between the digital component and the other component are described in Section 2.3. Section 2.4 reviews operationalisations of the accessibility components in virtual and hybrid accessibility measures.

2.2. *Interactions between the individual and social component and other components*

The 2004 model departs from individuals. However, many people live in multi-person households, and household members can help overcome accessibility barriers (Dugundji et al., 2011). This also implies that many travel-related decisions are made at the household level – see Hu et al. (2023) for a literature review. This relates to residential locations, work locations of household members, school locations of children, car ownership, and household task and activity allocation. Consequently, household characteristics influence accessibility levels as addressed in the 2004 model. The social dimension, however, exceeds the household level. Access to various opportunities is also affected by social networks (e.g., family, friends, and neighbours). For example, neighbours doing groceries for people who are less mobile or driving people who cannot drive to specific locations, such as a hospital. The social component can also be organized and institutionalized in a more advanced way, conceptualized as 'commoning accessibility' (Pucci et al., 2025), a concept in which accessibility is collectively managed and designed by a group of collaborating actors. The importance of the social dimension is underpinned by social practice theory (Shove et al., 2012; Spotswood, 2016). A social practice can be how people interact and collaborate in (location-based or online) activities, and that interaction can influence people's accessibility levels. Moreover, social practices can imply that individual accessibility becomes less important, e.g., when neighbours or friends pick up each other's children at school. A lack of social practices can also reduce individual accessibility, creating barriers to travel. For example, Martinez et al. (2024) examined the requirements of disadvantaged groups concerning the use of shared mobility services at mobility hubs and found that several disadvantaged groups need the support of someone who can give them the necessary information to travel or use the service and help them book a service or buy a ticket. To the best of our knowledge, there are no studies that have attempted to operationalise household and/or wider social interactions in calculated accessibility measures.

The emergence of shared mobility platforms introduces social interactions within neighbourhoods, with households offering and using shared vehicles, creating interactions with the transport, land use and digital components. With the increase of shared mobility, opportunities to travel (access to vehicles) can also partly depend on the offering and use of shared vehicles by other people in the neighbourhood (e.g., car sharing) or beyond the neighbourhood (e.g., ride sharing). This implies that non-car-owning households can increase their opportunities to travel by car by joining (peer-to-peer; P2P) car-sharing schemes. The supply and use of car sharing vary significantly across Europe. In France, P2P car sharing schemes are very popular, whereas in Germany and Belgium most shared cars operate in a business-to-consumer (B2C) model (Münzel et al., 2020). Moreover, the supply of P2P also positively influences the supply of (B2C) car sharing schemes in European cities, and vice versa Münzel et al. (2020). In the Netherlands, about 10% of the Dutch population has borrowed a car from family and friends in the past three years, and about 5% have used a shared car from a P2P platform (e.g., Snappcar) or shared ownership scheme (Goudappel, 2025). The accessibility impact of peer-to-peer or community-driven shared mobility is the combined effect of the transport and individual and social components. However, these opportunities will benefit some more than others. Opportunities for car sharing are not spatially equally distributed, and thus potentially also introduce interactions with the land use component. Pede and Staricco (2021) show, for example, in a study on three Italian cities that car sharing schemes are more developed in central urban areas, and less developed in deprived areas, and Münzel et al. (2020) show that P2P carsharing is popular in cities with many highly educated inhabitants. The individual and social component also interacts with the temporal component. For example, when parents pick up each other's children from a primary school or kindergarten in case of a delay of a parent.

2.3. Interactions between the digital component and other components

Digital technologies mutually interact with the transport component, and in each direction, in multiple ways. First, digital technologies influence travel resistance in several ways. A traveller can access (personalised) travel information before and during the trip using mobile devices (e.g., smartphone, laptop, tablet), and as a result, reduce access time, optimize route and mode choice. Route planning, which was, before the era of ICT, an individual task based on maps and personal experience, has become ICT-based and increasingly situation-aware, taking congestion into account and route alternatives proposed by algorithms that can forecast traffic in real time (e.g., Liebig et al., 2017). However, this does not mean that travel information is always accurate. Conventional planners such as Google Maps do not incorporate the availability and locations of shared vehicles. Ruß and Gust (2023) show, based on a case study in the city of Hamburg, that a reliable intermodal route planner including public transport, shared modes, cycling, and walking can reduce travel time on average by 9% in comparison to a conventional planner, and for single routes, these savings can reach up to 37%. Second, the emergence of smartphones opened the way to several new mobility services and opportunities to travel, including bike sharing, ridesharing, car-sharing services, on-demand taxi (Uber and all its followers), and transit services. Peer-to-peer (P2P) business models allow car owners to add their private car to a car-sharing platform, basically at zero marginal cost. Shared mobility has become a common phenomenon in many countries (e.g., see Coenegrachts et al., 2024). Third, digital technologies allow travellers to use travel time as worthwhile time (e.g., making phone calls, online working), creating a positive utility of travel, or at least decreasing the negative utility of travel. Molin et al. (2020) examined the impact of onboard activities on the value of time of train users in the Netherlands, and they concluded that the value of time due to onboard activities is 30% lower for commuters and almost 50% for leisure travellers. The transport component can also directly influence digital accessibility. For example, many public transport operators offer on-board free Wi-Fi on local, regional, and cross-border connections (e.g., SNCF in France, Deutsche Bahn in Germany, Trenitalia in Italy, Dutch railways in the Netherlands), facilitating online on-board activities.

There are two-way linkages between the digital and land use components. Digital technologies result in large-scale transformations across multiple sectors, affecting the land-use component directly and indirectly via the land-use component of accessibility. The quality of ICT connections has proven to influence national and regional economic developments. Based on a literature review, Yousefi and Dadashpoor (2020)conclude that ICTs have significant effects on the elements that shape urban spatial structure, including spatial and physical aspects and the distribution of everyday activities such as housing, leisure, and work. Based on a review of empirical studies, Briglauer et al. (2024) conclude that there is a large body of evidence on the impact of basic and high-speed broadband infrastructure on economic growth and employment, but subject to diminishing returns beyond a certain broadband quality level. The land use component also influences the digital component. For example, areas with low population densities, such as rural areas, have less well-developed digital infrastructures. This urban-rural digital divide is well studied in the literature (e.g., Salemink et al., 2017; Feurich et al., 2024), showing that rural communities are most in need of improved digital connectivity to compensate for their remoteness, but they are the least connected (Salemink et al., 2017).

Authors in the early 2000s already suggested that ICT could enable a new, virtual mobility, enabling an Internet-based increase in accessibility (Kenyon et al., 2002). Here, we will briefly discuss the role of teleworking, e-shopping, and digital healthcare that shape land use developments. Teleworking increased tremendously during the COVID-19 pandemic (e.g., see for an overview of the literature Olde Kalter et al., 2023), and post-pandemic studies show (part-time) telework arrangements may remain at an elevated level (Asmussen et al., 2024). *E*-shopping affects retail accessibility directly, but also indirectly via the land use and temporal component. Delivery is often free, and sometimes very fast, offering free delivery within 24 h, and transforms physical trips to online purchases, impacting locations of activities and shops, which caused a seismic shift in the organization of the retail and logistics sectors (Beckers et al., 2021). The impact of e-shopping on physical travel has already been a topic of study for decades (e.g., see Mokhtarian, 2004; Colaço and de Abreu e Silva, 2023). E-shopping also affects the locations of shops and activities, as it requires retailers to rethink retail strategies and locations. Fun shopping, which refers to the leisure aspect of retailing, is usually enjoyed in historical urban central places. Studies in the UK, for example, show that growth in E-commerce increased the number of vacant shops, particularly in small town centres and small retail centres (Dolega and Lord, 2020). Out-of-town strip malls or ribbon developments accommodate so-called ‘run’ shoppers who focus on efficiency and rationality, in contrast to ‘fun’ shopping usually enjoyed in historical urban central places (Beckers and Verhetsel, 2023). The digitalisation transformation in the healthcare sector has direct impacts on healthcare accessibility and indirect impacts via the land use component. The COVID-19 pandemic also triggered the development of various e-health, telemedicine, and/other telehealth solutions for chronic disease patients (Bitar and Alismail, 2021). There is increasing interest in electronic doctor consultation and telemonitoring systems, allowing patients to receive healthcare at home, as an alternative to in-hospital admissions, providing access to healthcare without the need to travel (e.g., Scherrenberg et al., 2023). The impacts on travel are understudied; however, a literature review study on e-health in rural areas in Australia and Canada showed that 90% of studies reported positive impacts on travel time, travel cost, and increased access to healthcare services (LeBlanc et al., 2020). A transition from physical health care to online thus directly impacts healthcare accessibility, but there are also implications for the location and capacity of health care facilities, resulting in indirect impacts via the land use component. These indirect impacts can be expected to grow in importance with the increase in healthcare providers implementing e-health strategies.

There are two-way interactions between the digital component on the one hand, and the individual and social components on the other hand. Digitalisation can have an impact on the needs and wants of people, but also the necessary capabilities and ability to access locations, transport modes, and services. People might, for example, want to go to a concert they are aware of thanks to ICT. ICT can also harm people's abilities to travel. For shared mobility options, such as ride sourcing, car and bike sharing, not only is digital access to services the default option, but it is also nowadays frequently the only option. This can increase transport disadvantage for some groups in society. Durand et al. (2021) conclude in a literature review that vulnerability to digitalisation in transport services exists along dimensions of age, income, education, ethnicity, gender, and geographical region. Eurostat figures for 2023 show that about 56% of the EU population aged 16–74 had basic or above basic digital skills (Eurostat, 2025). Even in countries with relatively high digital skills, such as the Netherlands, a significant portion of the population has difficulties using travel-related apps or websites. Durand et al. (2024) find that 6 to 10% of car and public transport users seem to struggle with various aspects of digital skills (e.g., use of travel apps and websites to find information or planning trips).

There are several interactions between the digital and temporal components. Online activities such as e-shopping, teleworking, and e-health services reduce the need to travel, increasing available time for other activities, including travel to other activities, and reducing temporal constraints related to, for example, opening hours of shops.

2.4. Operationalisations of the accessibility components in virtual and hybrid accessibility measures

In the 2004 Geurs and van Wee paper, accessibility measures were classified into four categories, i.e., infrastructure-based, location-based, utility-based, and person-based approaches. Infrastructure-based measures describe the functioning of physical transport systems in terms of distance, travel time, and travel costs, and ignore the land-use component of accessibility. Note that, we ignore virtual infrastructure-based equivalents, focusing on describing the availability and quality of digital infrastructure, such as broadband connections. Location-based accessibility measures how easily people can reach spatially distributed opportunities from a specific point. Common location-based measures include the cumulative opportunities measure, the potential or gravity-based measure following Hansen's (1959) framework, the Shen index (Shen, 1998), and the equivalent two-step Floating Catchment Area (2FCSA). These measures are also frequently used to estimate digital and hybrid physical-digital accessibility to work, shops, and health services. However, in the literature, much less effort has been made to operationalise virtual or hybrid accessibility based on person-based, utility-based, or combined utility-based time-space measures. In the 2000s, several studies developed operationalisations of space–time and expanded classical time-geographic measures to include both physical and virtual worlds (Neutens et al., 2011). Shaw and Yu (2009) provided a theoretical framework to incorporate virtual space into space-time accessibility metrics. Ettema and Timmermans (2007) explored how travel information affects accessibility by extending the utility-based space-time framework. Lu et al. (2014)created a utility-based conceptual framework with numerical examples to measure how travel information and online activities impact accessibility. Compared to location-based approaches, these studies offer operationalisations and numerical examples, but to the best of our knowledge, have not been applied in empirical studies or other contexts. Table 1 presents an overview of operationalisations of the five accessibility components in studies aiming to measure (calculated) virtual or hybrid physical-virtual accessibility. The presented elements within each component are identified in Section 2.

From Table 1, a few general observations can be made. First, Table 1 illustrates the lack of studies that operationalise interactions between the digital and transport components. Only a few studies have been found to operationalise the impact of travel information on accessibility (Lu et al., 2014; Cavallaro and Dianin, 2020). Second, shared mobility has become a common phenomenon in most countries but is rarely incorporated in accessibility studies. For example, there are many cycling accessibility studies in the literature (for a review, see Vale et al., 2016), but surprisingly, only a few of them have incorporated bicycle sharing systems in operational measures of cycling accessibility. Song et al. (2020) present one of the rare studies examining the impact of bike sharing services on a gravity-based cycling accessibility measure, based on geo-location data collected from two major bike-sharing companies in Beijing. Moreover, there is a rich literature on measuring accessibility to various opportunities by car, but the impact of car sharing is understudied.

Second, the table illustrates that most studies examining hybrid and virtual accessibility components have focused on teleworking and telehealth. However, compared to the rich literature on physical job and healthcare accessibility, the number of studies is small. Shen (1999) was probably the first to reconceptualise a physical potential job accessibility measure as a hybrid potential job accessibility. The study distinguishes between workers who have and do not have telecommunication capabilities, and impedance associated with travel is reduced if workers can telecommute. Following Shen's specification, Muhammad et al. (2008) estimated job accessibility in virtual and physical space. Recently, Cavallaro and Dianin (2022) developed a hybrid job accessibility model incorporating (partially or entirely) in-person and remote working opportunities, and Van Lent et al. (2025)further developed a hybrid job accessibility model to estimate individual accessibility for the

Table 1
Operationalisations of the components of calculated accessibility in virtual/hybrid accessibility studies.

Component/element	Operationalisation of calculated accessibility
Transport	
Travel information	Utility-based accessibility model (Lu et al., 2014) with travel information and teleshopping as variables. Public transport accessibility with availability of information types (online, offline, mobile) and information integration as variables (Cavallaro and Dianin, 2020)
New mobility services	Bicycle sharing impact on cycling accessibility (Song et al., 2020), impact of on-demand bicycle and car sharing at mobility hubs on job accessibility (Frank et al., 2021)
Travel time and cost of physical travel	Travel time and/or monetary cost, value of time, in hybrid accessibility model (e.g., Cavallaro and Dianin, 2022; Chen et al., 2024a)
Land Use	
Teleworking / hybrid working	Spatial distribution of teleworkable jobs as opportunities in virtual dual cost accessibility model (Chen et al., 2024a) and potential hybrid job accessibility measures (e.g., Shen, 1999; Muhammad et al., 2008; Cavallaro and Dianin, 2022; van Lent et al., 2025)
Teleshopping /hybrid shopping	Spatial distribution of the level of e-shopping, number of delivery points per 10,000 people (Shao et al., 2022)
Telehealth	Spatial distribution of hospital telehealth services (e.g., Alford-Teaster, 2021) and primary care physicians with telehealth facilities (Wang et al., 2023; Liu et al., 2023) in virtual catchment area of 2-step floating catchment area (2SFCA) accessibility model
Individual and social component	
Individual characteristics/ population segmentation	Potential hybrid job accessibility measure with segmentation across job types and sectors (van Lent et al., 2025); telehealth accessibility for rural, urban, various racial-ethnic groups and households under poverty (Liu et al., 2023)
Temporal component	
Shared mobility	24 h variation in gravity-based cycling accessibility based on shared bicycle usage (Song et al., 2020)
Shopping	Shipping and last-mile delivery times, duration of in-store shopping (Chen et al., 2024b)
Digital component	
Cost	Economic costs of working at home, comprising working space, utility fees, internet and device costs, and potential reduction of wages as impedance factors in a virtual job accessibility model (Chen et al., 2024a); Daily cost of remote work, internet subscription, energy cost, material costs as impedance factors in a hybrid job accessibility model (Cavallaro and Dianin, 2022). Cost of online shopping, including waiting time, delivery cost, shopping time, cost of online shopping goods, discounts, in virtual shopping cost (dual access) measure (Chen et al., 2024b)
Availability and quality of digital infrastructure	Binary decay variable for broadband internet availability at demand and health supply locations (e.g., Alford-Teaster et al., 2021) or broadband subscription rate and affordability (Liu et al., 2023) in virtual 2SFCA healthcare accessibility model, Decay parameter (between from 0 to 1) reflecting maximum internet speed registered in a hybrid potential job accessibility model (e.g., Cavallaro and Dianin, 2022)

entire Dutch workforce. Chen et al. (2024a) estimated physical and virtual job accessibility separately.

The conceptualization of virtual accessibility via telehealth has received growing attention in health geography literature to measure the impact of telehealth on healthcare accessibility. The two-step floating catchment areas (2FCA) method is widely used to measure physical accessibility to healthcare, capturing the supply–demand interaction strength by a distance decay effect. Alford-Teaster et al. (2021) introduced an adapted two-step virtual catchment area (2SVCA) method to measure access to hospital telehealth services, where the virtual connection strength is measured by the availability of digital infrastructure (broadband). These measures assume telehealth has a spatial component, as telehealth often works as a supplementary consultation to reduce travel burdens for patients making physical visits (Wang et al., 2023). The method has been used by others in several studies, including primary care physicians with telehealth facilities (Wang et al., 2023; Liu et al., 2023).

Developing teleshopping and hybrid physical/virtual accessibility measures creates several complexities, and only a few operational measures are found in the literature. There is also not much research on the role of teleshopping/e-shopping and its interactions with physical accessibility. Major challenges in measuring teleshopping are related to the measurement of shopping opportunities in virtual space, and the spatial and transport components of online shopping, such as online stores, delivery points, and local delivery stores. Access to food delivery, for example, depends on the catchment area of food delivery services. Shao et al. (2022) developed a general spatial model to explore the role of virtual and physical accessibility in the spatial distribution of e-shopping in China, where virtual accessibility is measured based on the availability of Internet access and the availability of delivery services. Chen et al. (2024b) developed a virtual shopping accessibility measure based on the so-called dual (or reciprocal) access, measuring the travel cost required to access a set number of opportunities (Cui and Levinson, 2019). Chen et al. (2024b) advocate this approach to sidestep the measurement of equivalence of opportunities in both physical and virtual domains, and to shift the focus to the expense of ensuring goods arrive at the demanded location (e.g., food at home), rather than at the supplied point (e.g., a store or warehouse).

A third observation is that interactions between the individual and social component and digital components are not often included. Some studies have examined hybrid or virtual accessibility for specific population segments. Van Lent et al. (2025)show, for example, that accessibility and job competition for hybrid jobs differ strongly by occupational class, e.g., workers in commercial, technical, and transport and logistics professions face a decrease in job accessibility if job competition is considered. Liu et al. (2023) show that telehealth accessibility of primary care physicians is significantly lower for people living in rural areas, racial-ethnic groups, and households under poverty. We did not find any study that explicitly considered digital skills as part of the individual component of accessibility.

3. A five-component conceptual model for perceived accessibility

3.1. A conceptual model for perceived accessibility

Calculated accessibility, as described in section 2, is based on the spatial distribution of activities and the impedance to overcome spatial separation. Calculated accessibility metrics have been criticised for assuming that individuals know all the costs and benefits of all the different alternatives (Aoustin and Levinson, 2021) and have the same ability to use the transport system (Palm et al., 2025), and for ignoring perceptions of accessibility (e.g., Pot et al., 2021). To address these criticisms, the concept of 'perceived accessibility' has received increasing attention in accessibility studies; see Negm et al., 2025, for a recent literature review. Perceived accessibility is defined in various ways in the literature, and many definitions focus on the outcome of a transportation system and how it connects to someone's ease of living (see Negm et al., 2025). The developers of the Perceived Accessibility Scale, which serves as a starting point for empirical studies on perceived accessibility, define perceived accessibility in terms of "how easy it is to live a satisfactory life using the transport system" (Lättman et al., 2016b, p. 37). We disagree with this definition, firstly because it does not separate between perceived accessibility and its effects (a satisfactory life), and secondly because it only recognizes the importance of the transport system, ignoring the land use system. We agree with the studies that have built on the accessibility definition from Geurs and Van Wee (2024), excluding elements of satisfaction or ease of living (e.g., Pot et al., 2021; Negm et al., 2025). Pot et al. (2021, p. 2), for example, defined perceived accessibility as "the perceived potential to participate in spatially dispersed opportunities". We follow this approach but explicitly link our definition to the five components of accessibility, including the digital component. Few studies have examined the role of the digital component in perceived accessibility, a notable exception being Liu et al. (2021), who studied smartphone-based mobility services (e.g., Liu et al., 2021). These studies have explicitly included the digital component in definitions of perceived accessibility. Here, we define perceived accessibility as *the perception of individuals of the extent to which land-use, transport, and digital communication systems enable individuals to participate in activities and reach destinations online and/or through a (combination of) transport mode(s), at various times of the day.* Note that, like our definition of calculated accessibility, we consider activities that do not have a functional physical equivalent not relevant for perceived accessibility analysis but have not explicitly excluded these activities in our definition to avoid complexity.

There are two options to conceptualize perceived accessibility. The first option is to stick to the conceptualization of Fig. 1 and make explicit that perceptions of all five components are part of the individual and social component, more specifically, the individual part of that individual and social component. A motivation for this conceptualization could be that perceptions are, by definition, perceptions of individuals. The other option is to make explicit that perceptions apply to all components of our accessibility model, as conceptualized in Fig. 2. The advantage is that not only is it clear that perceptions apply to all components, but also to interactions between those components. Below we explain this second option.

In the literature, Pot et al. (2021) already provided a conceptual model of perceived accessibility based on the 2004 core accessibility model. Here, we extend this model based on our five-component conceptual model but add 'perceived' to the five components, to reflect that perceived accessibility is shaped by people's perceptions of opportunities provided by the land use, transport and digital systems, and people's perceived ease to engage with those opportunities. For communication reasons, in this paper, we do not integrate calculated and perceived accessibility in a single conceptual model but developed a separate conceptual model for perceived accessibility. The five-component perceived accessibility model is visualised in Fig. 2 and summarized here. For an elaborate discussion of the perceived land use, transport and temporal accessibility components, please refer to Pot et al. (2021).

The perceived land use component reflects the perceived amount, quality and spatial distribution of opportunities supplied at each destination, and perceived competition for opportunities with restricted capacity, such as job and school vacancies and hospital beds. The perception of the amount, quality and spatial distribution likely differs from reality. This involves knowledge of available opportunities and their locations (i.e., the declarative and relational components of spatial knowledge) and also perceived attributes of activity locations matter (Pot et al., 2021). People may under- or overestimate how nearby activities are, and people may not be interested in the nearest activity (De Vos et al., 2025). In addition, people might under- or overestimate competition for opportunities and choose other jobs, schools, or

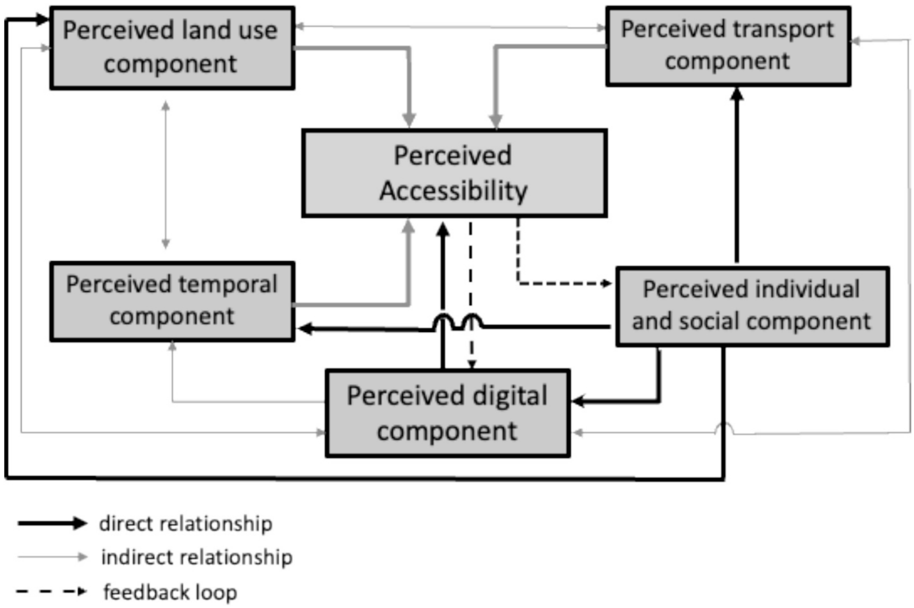

Fig. 2. A five-component conceptual model for perceived accessibility.

healthcare facilities as a result.

The perceived transport component reflects people's perceptions of travel options, travel times, costs and efforts, which are typically different from observed ones or travel planners. There is a rich literature on the under- or overestimation of reported travel times of chosen and non-chosen modes (e.g., Witlox, 2007; van Exel and Rietveld, 2010). For example, van Exel and Rietveld (2010) show that car drivers in the Amsterdam region in the Netherlands overestimate public transport commuting travel times by 50%, and the level of distorted perceptions strongly depends on actual public transport use.

Regarding the temporal component, people may under- or overestimate the temporal variation in accessibility, such as travel time during rush hours or punctuality of public transport, and opportunities might not be available during specific times of the day. Finally, regarding the digital component, people can have different preferences to use or not to use travel information provided by digital tools such as smartphone apps or digital information screens.

The individual and social component interacts with the other four components. For example, people do not have the same travel abilities and preferences, e.g., not everybody can (easily) walk or cycle, have access to a car, want to travel by certain travel modes, or are not fully aware of the available travel options (De Vos et al., 2025). Individual capabilities, for example, also influence how information is gathered and interpreted. Individual processing mechanisms result in a mental image of the environment. This cognitive environment, often incomplete, distorted and coloured through filtering and biased processing, which is shown in studies using mental sketch-mapping techniques (Pot et al., 2021). Of course, socio-demographics like age, gender and income are not subject to perceptions that diverge from real age, gender and income. But perceptions of the ability to use digital tools can differ from the real capabilities of people to use such tools. And the perceptions of the individual and social component can also play a role. For example, disadvantaged groups might over- or underestimate barriers to travel and the level of support needed to travel, for example, with shared modes and public transport. See Martinez et al. (2024) for an in-depth exploration of barriers and requirements of disadvantaged groups related to the use of shared mobility at mobility hubs. Moreover, people might over- or underestimate the availability of travel support from people in their social network, in general or for specific trips.

The conceptual model shows direct relationships between the individual and social component and the other four components, indirect relationships, and one feedback loop between perceived accessibility and the individual and social component. Perceptions of the different components interact. For example, perceptions of distances (land-use) are likely to influence perceptions related to travel resistance (transport system) (Pot et al., 2021). If people overestimate the temporal variation in accessibility, such as travel time during rush hours or punctuality of public transport, it will also affect perceptions of the effort to travel to activity locations and thus location choices. The latter reflects bi-directional relationships between perceived accessibility and travel preferences, shown by Mehdizadeh and Kroesen (2025) using a two-wave cross-lagged panel model. They found that travel mode use has a larger impact on perceived mode-specific accessibility than the reverse effect.

The difference between perceived and calculated accessibility probably strongly relates to (parts of) accessibility components. For example, a person very likely knows the opening hours of the supermarket nearby her residential location, but maybe not the opening hours of a supermarket near her holiday destination. And travel times by car of frequently made (commuting) trips depending on time of day and day of the week, are probably also well known to people, but travel times for a trip not made before are less certain, and perceptions could easily differ from actual travel times. ICT can reduce the discrepancies between perceived and actual opening hours or travel times, at least to some extent.

3.2. *Operationalisations of the components of accessibility in perceived accessibility studies*

Negm et al. (2025) recently provided a systematic literature review based on 45 studies discussing perceived accessibility. Perceived accessibility studies in the literature are all based on stated preference surveys, but the perceived accessibility measure varies across the studies based on variations in the number of survey questions/statements and scales used (i.e., binary, 3-point, 4-point, 5-point, 7-point Likert scales). The Perceived Accessibility Scale (PAC) is the most common measure for perceived accessibility, originally developed by Lättman et al. (2016a) as the mean value of four 7-point Likert questions that assess the public transport system's impact on the ability, ease, and satisfaction of participation in activities, and the ability to live as one wants if public transport is the only mode of travel. In a later study, the PAC score was generalised to overall perceived accessibility of residential areas regardless of the transport mode, by removing the specific mode in the questions (Lättman et al., 2018).

Several studies have examined differences between calculated and perceived accessibility measures (e.g., Aoustin and Levinson, 2021; El Murr et al., 2023; Lättman et al., 2018; Pot et al., 2021). These differences can firstly arise, as noted in section 3.1, from inaccuracies in an individual's awareness of physical and virtual opportunities provided by the transport, land-use and digital systems. Second, there can be inaccuracies in the calculated measures (not accounting for certain components that are important in people's experiences) or inaccuracies in perceived accessibility measures. Regarding the latter, Negm et al. (2025)conclude that empirical work on perceived accessibility is emerging, but significant ambiguities surround its definition and measurement. In particular, the authors state that measurements of perceived accessibility should be isolated from life satisfaction to avoid conflation with well-being concepts.

Table 2 presents an overview of the different elements of the five components that are incorporated in operationalisations of perceived accessibility studies in the literature. Note that, consistent with our definition of perceived accessibility, Table 2 does not include components that relate to quality-of-life measurements.

Current studies on perceived accessibility focus on the perceived land use and transport components but lack attention to the temporal component and digital component of accessibility. Few studies have explicitly added survey statements on travel information or ICT availability, e-shopping, or smartphone-based shared mobility services such as bike sharing and ride hailing. Studies on the impacts of telecommuting, teleshopping, or the various e-health, telemedicine, and/ other telehealth solutions on perceived accessibility of healthcare are lacking. Regarding the land use component, perceived accessibility studies focus on measuring the ease or satisfaction of accessing activities or amenities but typically lack attention to the availability of opportunities. In a survey conducted in the Netherlands, Pot (2025) examined links between perceived accessibility and perceived sufficiency statements, such as “enough schools”, “good provision of opportunities to go out”, “good provision of health facilities', and “enough supermarkets”. Mainly in rural areas, discrepancies are found between perceived accessibility and perceived availability of opportunities.

In addition, ICT can be a mediator for perceived accessibility: the perception of a certain level of physical accessibility could depend on the availability of ICTs to show which physical options are available.

Table 2
Operationalisations of the components of accessibility in perceived accessibility studies.

Component	Operationalisation of perceived accessibility - examples
Perceived transport	
New mobility services	Perceived accessibility of smartphone-based mobility services (dockless bike-sharing, ride hailing) (Liu et al., 2021); Perceived accessibility of carpooling (Friman et al., 2020) Perceived accessibility to different activities of dockless bike-sharing (Chen et al., 2022), Attitude to demand-responsive transport (Pot et al., 2023)
Travel distance, time and cost	Travel distance (Pot and Piesch, 2024), Travel time, perceived public transit service quality, and frequency of use (Lättman, 2016b); Perception of travel time by walking, bike, e-bike, public transport and car (Aoustin and Levinson, 2021)
Other impedance factors	Perceived safety, comfort of public transport (Lättman et al. (2016b)
Perceived land use	
General	Perceived accessibility of daily activities (Lättman et al., 2016a, 2018; Pot et al., 2023; Palm et al., 2025)
Specific land uses	Perceived accessibility to parks (El Murr et al., 2023; Ma et al., 2025); Potential job accessibility, distance to various amenities as variables in perceived accessibility (Pot et al., 2023); Perceived availability of neighbourhood amenities (schools, retail, health, sports, supermarkets) (Pot, 2025)
Urban/rural areas	Dense, urbanized environments increase the sense of accessibility (Tanimoto and Hanibuchi, 2021); perceived decline of rural amenities (Pot et al., 2023)
Individual and social component	
Individual characteristics/ Population segmentation	Age (Lättman et al., 2016b; Ryan et al., 2016) and other household, and personal characteristics are associated to perceived accessibility (Olsson et al., 2021; Pot et al., 2023); Car ownership, perceived public transport skills (Pot et al., 2023), positive attitude towards modes (Pot et al., 2023)
Digital skills	The ease of using smartphone-based services for online food, bike sharing, ride hailing, public transport ticketing (Liu et al., 2021)
Social interactions	Perceived social norms and perceived neighbourhood social environment (Al-Rashid et al., 2021); Social support from family and friends to use dockless bike-sharing systems (Chen et al., 2022); Neighbourhood cohesion (Tanimoto and Hanibuchi, 2021); Social network for ride sharing (Pot et al., 2023)
Perceived temporal component	
Travel time variation	Punctuality of public transport (Lättman et al. (2016b)
Perceived digital component	
Travel information	Public transport travel information (mobile app, website, bus stop) (Lättman et al. (2016b)
ICTs availability	Perceived quality of internet access (Pot et al., 2023)

4. Practical implications for accessibility analysis

In this section, we discuss the most important practical implications of our five-component conceptual model for accessibility analysis.

4.1. The digital component

The importance of the digital component for accessibility (including applying accessibility in policy and planning) depends on the question of the extent to which ICT is a substitute for physical accessibility or is complementary to physical accessibility. ICT can be a good substitute for physical accessibility in case of some forms of health care, some jobs (or at least some parts of jobs that can be do online), and some forms of education. But in other cases, like surgery or going to a hairdresser, ICT is not a substitute at all. The more ICT can be a substitute for physical accessibility, the more important the digital component is for overall accessibility. Complementarity is a bit more complicated. Nevertheless, for some tasks online and onsite task components can be complementary, such as in case of some forms of education which can be partly done online and partly onsite. Due to this complementarity students could choose a more remote place of education knowing that they only must travel to school or university once or twice per week. So, complementarity influences options to follow education. The same applies to jobs that can partly be done online and partly onsite. The extent to which substitution and complementarity influence accessibility levels depends on individual characteristics, because for the same activities not all people will be equally able or willing to engage in digital activity forms.

For the inclusion of substitution and complementarity aspects into operational measures that combine physical and digital access, we would recommend taking the theory of constant travel time budgets as a point of departure (see, for example, Mokhtarian and Chen, 2004). The resistance component of accessibility measures could be lowered proportionally to the reduction in travel time (or travel resistance) that can be substituted by ICT. Note that a reduction in the resistance component increases the number of options within access more than proportionally. Assuming a homogeneous distribution of activity locations over space, halving the resistance component increases the number of options within access by a factor of four.

But one can discuss whether it is preferred to combine physical and virtual accessibility in one measure or to distinguish separate measures for both types of accessibility. Both positions are possible and the choice depends on the research questions(s) at stake. In the literature, several hybrid accessibility measures have already been developed examining commuting and shopping, as described in section 2.4. In practical applications, separate measures of physical and virtual accessibility can also be useful. This is similar to the typical practice of estimating mode-specific accessibility. To combine physical and virtual accessibility, existing methods used to combine accessibility by different modes can be explored (see below). However, combining options is tricky, and the question would be what it means to have online options available and to what degree they are substitutes for having physical access. Questionnaires asking people about physical and virtual accessibility, and the extent to which for them, virtual accessibility can be a substitute for physical accessibility, can be used to decide if both types of accessibility should be presented separately or not, for what opportunities, and for whom. An interesting avenue for future research would be to conduct Latent Class Cluster Analysis or estimate Latent Class Choice Models (e.g., see Molin et al., 2016). We guess there are latent classes of people with respect to the integration or not of the digital and physical aspects of accessibility, classes that are probably related to at least age (generation), education level, and attitudes.

In case of perceived accessibility, the relative importance of physical versus virtual access, including the perceptions of substituting onsite by virtual accessibility, can be explored by questionnaires making use of Likert scales. The results can be used for perceived accessibility measures that combine onsite and online accessibility. Again, Latent Class Models are an interesting avenue for future research.

4.2. Perceived accessibility

Here are now several papers on perceived accessibility, some of which are referred to above. Here, we first focus on an important question: what to do if perceived and calculated accessibility significantly differs? On the one hand, one could argue that planners should make use of perceived accessibility levels, because it is perceived accessibility that matters. On the other hand, is this fair? Is it OK to provide people with lower levels of accessibility because they perceive their level of accessibility as higher than other people in the same position? Especially if people are involuntarily faced with a low level of calculated accessibility, like in many rural areas, it seems unfair to us to base policies on perceived accessibility levels.

4.3. Aggregating over modes and destination types or not

The question of aggregation of accessibility measures over modes and destination types is an important one, but in the literature, there is no consensus yet. Levinson and Wu (2020), for example, discuss different methods to generalize accessibility over modes and destinations, and their difficulties. We first start with the question: should applied accessibility research and planning make use of mode-specific accessibility calculations, or should accessibility be aggregated over (dominant) modes? This question is relevant for both calculated and perceived accessibility.

The answer depends on the research or policy question at stake. In most cases, mode-specific approaches will do the job, because many people will rely on one or a few dominant modes. For example, a person without a car relies on public transport and active modes. Car owners might make most trips longer than those nearby by car. To give a practical example: for transport planning purposes, we argue that there is nothing wrong with calculating accessibility by bike if the aim is to plan cycling infrastructure.

But to understand the role of accessibility in residential choice, prices of dwellings, or planning the location of a new hospital, combining accessibility over different modes is probably more useful, because this role will probably be assessed over all people and all modes available. A kind of aggregate accessibility measure might then be preferable. The weighing of different modes for different destination types can be based on empirical research showing the share of each mode for each destination type, and the share of frequencies over destination types. However, weighting by mode or frequency share may misleading results, as for example, overall accessibility will decrease if a slower option is added. In reality, users will not necessarily be worse off in this case (Levinson and Wu, 2020). Another option is to select the fastest mode for each origin-destination pair. A third option, especially for perceived accessibility, is to ask people questions about their perceived levels of accessibility: do they give answers for one mode, for multiple modes or more intuitively over several modes available?

For questions like the impact of accessibility on residential choices, or prices of dwellings, it is even thinkable that destination types are aggregated, because as far as accessibility is concerned, people probably think in terms of access to multiple destination types. Then a question is: how to aggregate? Aggregations can be based on data: how frequently do people make trips to different destination types? But not all destinations are equally important for people. As an alternative and based on a discussion about theoretical underpinnings for such aggregations, Zheng et al. (2019) aggregated based on the importance of quality of life. Their accessibility analyses were mode-specific (walking, cycling, public transport, private motorized transport). It is even possible to aggregate over modes (as discussed above) and destination types.

4.4. Selecting accessibility indicators

Finally, we briefly reflect on selecting accessibility indicators for practical purposes. Of course, the indicators should match the practical needs in the first place. Next, we repeat what we wrote in our 2004 paper (page 130) about more general criteria: the choice for accessibility indicators to be used for practice should be made based on four criteria: '(1) theoretical basis, (2) operationalisation, (3) interpretability and communicability, and (4) usability in social and economic evaluations.'

5. Conclusions and directions for future research

5.1. Conclusions

This paper updated the 2004 accessibility definition and conceptual model of Geurs and van Wee (2004). It developed five-component conceptual models of calculated and perceived accessibility, where (perceived) accessibility depends on the (perceived) transport system, the (perceived) land use system, (perceived) digital infrastructure and technologies, the (perceived) temporal component, and characteristics of people and their social interactions, plus many mutual interrelationships. The addition of the digital component of accessibility is a major extension of our conceptualisation of calculated and perceived accessibility. However, compared to the rich literature on physical accessibility, the number of accessibility studies examining the direct impacts of digitalisation on calculated and perceived accessibility is understudied. Existing studies primarily focus on the impacts of teleworking and telehealth on calculated accessibility. Moreover, the digital component interacts with all components of accessibility, but few studies in the literature are found to operationalise these interactions. The second main extension to the 2004 conceptual model is the addition of social interactions to the individual component of accessibility. The literature review shows that existing calculated and perceived accessibility studies, however, typically ignore social interactions within households and local communities, which can help to overcome accessibility barriers and influence perceptions of accessibility.

The paper reviewed operationalisations of calculated and perceived accessibility, which measure accessibility in different ways and show different perspectives on accessibility. Calculated accessibility estimations rely on secondary transport and spatial data, whereas perceived accessibility is estimated using Likert-scale statements in surveys to examine people's travel capabilities based on their daily experience. The cumulative opportunity, potential/gravity-based method, and the Shen-index (Shen, 1998) and equivalent two-step floating catchment area method are the most common measures to measure calculated accessibility to jobs, leisure, healthcare, and other purposes by different or combined modes. The results of these accessibility calculations generally provide an overall measure of accessibility levels and illustrate the theoretical number of different types of opportunities that can be reached. However, high levels of calculated accessibility can coincide with low levels of perceived accessibility, and vice versa, depending on, for example, the measure's match with individual needs and abilities (Negm et al., 2025). These differences can arise from (i) inaccuracies in an individual's awareness of physical and virtual opportunities provided by the transport, land-use and digital systems, (ii) inaccuracies in the calculated measures (not accounting for certain components that are important in people's experiences), or (iii) inaccuracies in perceived accessibility measures, as ambiguities surround its definition and measurement.

5.2. Directions for further research

There are many gaps in the knowledge that need further research. We first focus on four broad directions of research related to the main gaps in the knowledge in operationalising the digital and individual and social components of accessibility to measure calculated and perceived accessibility, accessibility and equity, and valuation of accessibility. Second, we discuss the implications for the valuation and evaluation of accessibility.

5.2.1. Research directions related to the five-component conceptual models for accessibility

5.2.1.1. Digital component of accessibility. Several directions of research can be taken related to the digital component of calculated and perceived accessibility. First, the direct impacts of digitalisation (including teleworking, e-shopping, e-health) on both calculated and perceived accessibility need further research. This is a challenging task. It is much easier to overview components and elements that determine virtual and hybrid accessibility, than to operationalise and formalize these measures in practice, including data collection and analyses, and modelling interactions with other components of accessibility. The COVID-19 pandemic triggered, for example, the development of various e-health, telemedicine, and/other telehealth solutions, but studies on the impacts of these digital services on calculated and perceived accessibility are lacking. Conducting in-depth e-health accessibility studies will require inter- and transdisciplinary collaborations between transport and health researchers and healthcare service providers, as both healthcare demand of (types of patients) and healthcare supply characteristics (e.g., digital infrastructure, capabilities of health professionals) need to be factored in.

Second, research is also needed to develop virtual and hybrid accessibility measures for teleworking and online shopping. Defining opportunities and spatial friction is complicated in the context of virtual access to jobs and shops. A promising approach to sidestep these complexities is the 'dual access' approach developed by Cui and Levinson (2019), which estimates the travel cost to access a fixed number of opportunities. Following this approach, Chen et al. (2024a) estimated a cost function for teleworking including wages and cost of working from home, e.g., office space, internet costs Chen et al. (2024b) estimated a cost function for online shopping including costs such as waiting time, delivery costs and time spent shopping online.

Moreover, for some needs and wants, people do not have to travel because goods or services can be delivered at home, physical or digitally, such as e-shopping and home care delivery. In other words: home delivery can be a substitute for having physical access to shops or healthcare. In such cases individual access to these services is substituted by the need of service providers to access the home locations. In case of such services what is relevant is the importance of changes in such substitution possibilities. So, for accessibility research an avenue for future research is to explore the extent to which the supply of home delivery services changes or can change.

Third, although shared mobility has become a common phenomenon in many countries, shared mobility services such as shared cycling and car sharing schemes are rarely incorporated in calculated accessibility studies and are also not common in perceived accessibility studies.

Fourth, existing studies have not examined interactions between the digital component and the other components of accessibility, which are challenging to include as they may involve long-run impacts (e.g., the quality of ICT connections has proven to influence national and regional economic developments). Van Wee et al. (2012) indicated that Stated Preference techniques (including stated choice) might be a fruitful way to estimate the interactions between ICT and calculated accessibility measures, allowing an estimate of the trade-offs and compensation options.

5.2.1.2. Individual and social component of accessibility. Several directions of research can be taken to examine the individual and social component of accessibility. First, in their review of perceived accessibility studies, Negm et al. (2025) state that research on the impact of individual characteristics on perceived accessibility has focused on age and gender, but lacks attention for household composition, income, employment status, car ownership, and disability gained less attention. They also state that there is little consistency in the results concerning travel behaviour, residential choice and perceived accessibility.

Second, digital skills are growing in importance, as with the expanding role of shared mobility, travellers must rely on smartphones that are typically needed to use app-driven forms of shared mobility. Studies that explicitly considered digital skills as a factor in calculated accessibility measures are lacking and rare in perceived accessibility studies. This is probably related to data availability, as questions to determine mobility-related digital skill levels are not common in travel surveys, and standard socio-economic characteristics such as age, education, and income are found to be related to digital skills but only partly explain digital skills (e.g., see Garritsen et al., 2025; Durand et al., 2024).

Third, the impact of social interaction and social networks on (perceived levels of) accessibility deserves more attention. Existing calculated accessibility studies ignore social interactions within households and local communities. Dependency on others to travel and the use of emerging and shared vehicles are typically not measured in current travel surveys, which are the basis of many accessibility studies. A few perceived accessibility studies have included statements on social interactions and networks; however, the direction of linkages needs further work. Pot et al. (2025) find that having a social network through which lifts can be easily arranged is positively related to perceived accessibility in rural areas, but feedback mechanisms are likely in place: those with stronger networks have more opportunities to participate in activities, but participation may also contribute to the quality of social networks. Furthermore, as Van Wee (2021) argues, the importance people attach to a certain level of accessibility can be influenced by the levels of accessibility that other people have, an influence that is addressed by the concept of positional goods (Hirsch, 1977). Structural equation modelling could prove useful to explore relationships between the different individual and social accessibility factors and their impacts on perceived accessibility.

5.2.1.3. Trip chaining. Most accessibility studies focus on access to destinations, assuming single destination trips with the origin of the trips being the residential location. The main exception is in space-time accessibility studies, which also consider trip chaining, taking residential and job locations as given. An interesting avenue for future research is to study accessibility assuming other origins than the residential location. Although most trips made have the home location as the origin (or destination for a return trip), it is relevant to also study access to destinations from other origins than the residential location. For example, Barboza et al. (2025) estimated space-time accessibility measures based on mobile phone call detail record data, illustrating large inequalities in access to public parks from home and work locations for low-income dwellers in the city of São Paulo. This is relevant in general, but certainly in the context of two of the main new conceptualizations presented above: the role of the digital component and perceived accessibility. The digital component allows people to stay for longer periods at other locations than the home location and work (part time of full time) online, digital nomads with changing temporary places to stay being an extreme example, increasing the importance of accessibility, assuming other origin locations than the residential location. And if trips have other origins than the residential location, people will on average be less familiar with the characteristics of the land use and transport system, so that perceptions of those characteristics are relatively more important than if the home location would be the origin. But because of the huge heterogeneity of other potential locations than the residential location, it is quite complicated to do such research in such a way that it is relevant for policy and practice. As a first step, research could study the frequency of other types of origins from which access to opportunities is important for people. A related avenue for future research is accessibility in case of trip chaining: combining multiple destinations in a chain of trips.

5.2.2. Research directions related to the evaluation of accessibility

The directions above relate to accessibility itself, which is the core of our paper. Evaluating accessibility is not the scope of our paper, but our paper has relevance for the evaluation of accessibility. The next two future directions focus on this evaluation: equity and the valuation of accessibility.

5.2.2.1. Accessibility and equity. Another suggested main direction of research is related to perceived equity measures. Since the publication of the 2004 paper, equity-related accessibility studies have received a lot of attention. For many land use and transport policies in general, but certainly those related to accessibility, equity effects are nowadays also important. See Van Wee (2022) for a discussion on accessibility and equity, and Lucas et al. (2019) for overviews of many ways in which equity can be measured. Many calculated accessibility studies also apply equity metrics, including using statistical measures such as the Gini index or Palma index, while few studies examine equity in perceived transport. Existing studies show that it is feasible to use perceived accessibility to identify potential inequalities. Zhu and Lucas (2025), for example, recently measured the fairness of the distribution of perceived accessibility for residents of affordable and commercial housing residents in Nanjing, China, and found statistically significant differences between perceived accessibility and calculated and perceived equity measures for the two groups of residents (Zhu and Lucas, 2025).

The potential of the capabilities approach as a transport justice framework base for equity analysis has been pointed out by several authors (see Vecchio and Martens, 2021, for a review), and perceived accessibility-related capabilities contribute to a person's well-being (e.g., Palm et al., 2025). Nielsen and Axelsen (2016) argue to extend the capability approach to capabilitarian sufficiency, accounting for the idea that justice is fulfilled when everyone has certain (basic) capabilities above a certain threshold. Related to accessibility, this implies policies are more equitable if more people experience sufficient accessibility, rather than some people with sufficient accessibility gaining more. However, there is a lack of consensus on thresholds for sufficient accessibility (Vecchio and Martens, 2021; van Burgsteden et al., 2024), and few studies on perceived accessibility have examined preferences for the number of opportunities within reach (e.g., Pot, 2025).

5.2.2.2. Valuation of accessibility. Finally, our last main direction of research is to explore links between perceived accessibility and the valuation of accessibility. Some studies have, for example, shown that having more options available reduces the added value of additional options being available (Maat et al., 2005; Del Mar Parra López et al., 2022). For example, if one already has two supermarkets within walking distance, the added value of having an additional third supermarket available nearby is probably relatively low compared to the first and second supermarkets. Moreover, people not only value options they use, but in some cases also options they do not use (yet), which is related to the concept of the 'option value'. Geurs et al. (2006, page 614) state that "option values arise when people place a value on having a transport option available that they might use only under unusual circumstances". For example, car drivers may value the availability of public transport in case their car breaks down. The concept of the option value cannot only apply to the transport system but also to the land use system: people can value opportunities being available even if they do not currently visit them, e.g., a park, museum, or a hospital. This relates to perceived sufficiency measures as explored by Pot (2025), showing that people can report high levels of perceived accessibility to local amenities, but still report the number of local amenities to be insufficient. This illustrates the need for more research in defining and measuring perceived accessibility and perceived equity measures.

CRediT authorship contribution statement

Karst Geurs: Writing – review & editing, Writing – original draft, Formal analysis, Conceptualization. **Bert van Wee:** Writing – review & editing, Writing – original draft, Conceptualization.

Declaration of competing interest

None.

Data availability

No data was used for the research described in the article.

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