9 Accessibility: perspectives, measures and applications

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9.1 INTRODUCTION

A principal goal of transport policy is to improve accessibility: the transport system should allow people to travel and participate in activities, and firms to transport goods between locations (from mining, via stages of production, to distribution centres and finally to clients, such as shops or other firms).

The concept of accessibility as a central force in land-use development is traced back by some authors to at least a century ago (e.g. Levine, 2020). Since the first definition of accessibility as the 'potential of opportunities for interaction' (Hansen, 1959: 73) accessibility has taken on a variety of meanings *see* for elaborate reviews of the literature Geurs and van Wee (2004), Levine (2020) and Levinson and Wu (2020). Confusion in understanding of accessibility, according to Wu and Levinson (2020), often arises from the differences in the intellectual heritage in the various disciplines, the different mathematical formulations employed, the different language and words employed to describe related concepts, and the different aims each access measure hopes to achieve. This is problematic because the choice and operationalization of an accessibility measure may strongly affect the conclusions on accessibility.

Furthermore, Handy and Niemeier (1997: 1192) have stated that 'a distinct gap currently exists between the academic literature and the practical application of accessibility measures'. This statement is still valid today. Studies in Europe and North America highlight that although practitioners typically are convinced that comprehensive accessibility measures are useful in the planning practice, many do not use them in their work. A lack of knowledge and data, organizational barriers, and lack of institutionalization of accessibility measures and tools are the main causes of the implementation gap (Silva et al., 2017; Boisjoly and El-Geneidy, 2017).

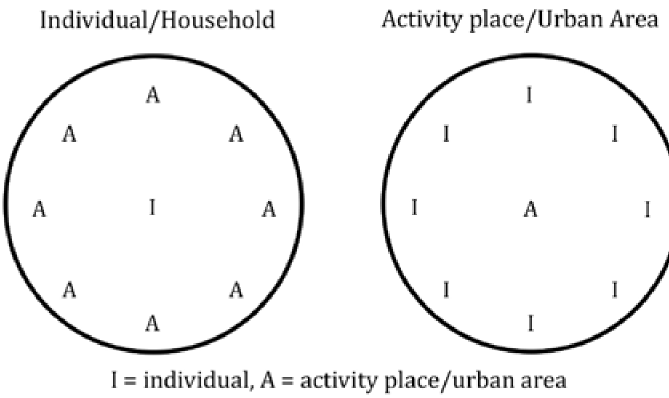
In this chapter we describe the different perspectives on accessibility (Section 9.2), the different components of accessibility (Section 9.3), the different means by which accessibility can be operationalized (Section 9.4) and the different criteria for choosing accessibility measures (Section 9.5). Section 9.6 describes the impact of ICT on accessibility analysis and measures and Section 9.7 addresses linkages between equity and accessibility. Two examples of accessibility measures are described in Section 9.8, illustrating how the choice and operationalization of accessibility measures can influence the conclusions. Finally, Section 9.9 presents the conclusions.

9.2 DEFINING ACCESSIBILITY

The definition of access, and thus its mathematical formulation, varies between studies and across disciplines (Wu and Levinson, 2020). At its core, as shown in Figure 2.1 in Chapter 2, accessibility can be measured as a product of (1) transport resistance, (2) locations, and (3) travel needs and desires. Following this conceptual framework, we can define accessibility from the perspective of persons (Geurs and van Wee, 2004: 128) and the perspective of locations of activities 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) at various times of the day (*perspective of persons*), and the extent to which land-use and transport systems enable companies, facilities and other activity places to receive people, goods and information at various times of the day (*perspective of locations of activities*).

The terms 'access' and 'accessibility' in the literature are often used indiscriminately. Here, 'access' is used when talking about a person's perspective: the area that a person can reach from his or her origin location to participate in one or more activities at destination locations at certain times. This is visualized in Figure 9.1. From the perspective of location, 'accessibility' is the catchment area from which people, goods and information from different locations can reach a specific origin location. The size of the area depends, for example, on the time, costs and effort that an individual is willing to accept (the transportation and individual component of accessibility; see Section 9.3). The size of the area varies in time (the temporal component of accessibility; see Section 9.3).



Source: Dijst et al. (2002).

Figure 9.1 Individual and location perspective on accessibility

9.3 COMPONENTS OF ACCESSIBILITY

Four components of accessibility can be distinguished: a land-use, transportation, temporal and individual component (Geurs and van Wee, 2004):

1. **The land-use component** reflects the land-use system, consisting of (1) the amount, quality and spatial distribution opportunities supplied at each destination (jobs, shops, health, social and recreational facilities, etc.), (2) the demand for these opportunities at origin locations (e.g. where inhabitants live), and (3) the confrontation of supply and demand for opportunities, which may result in competition for activities with restricted capacity such as job and school vacancies and hospital beds (see van Wee et al., 2001; see Section 9.8, the Shen (1998) accessibility measure). Find out more about the land-use component in Chapter 5.
2. **The transportation component** describes the transport system, expressed as the disutility for an individual to cover the distance between an origin and a destination using a specific transport mode. As with the transport resistance component (Chapter 6), it includes the amount of time (travel, waiting and parking), costs (fixed and variable) and effort (including reliability, level of comfort, accident risk, etc.). This disutility results from the confrontation between supply and demand. The supply of infrastructure includes its location and characteristics (e.g. maximum travel speed, number of lanes, public transport timetables, travel costs). The demand relates to both passenger and freight travel. Find out more about the transportation component (equivalently, the transport resistance) in Chapter 6.
3. **The temporal component** reflects the temporal constraints, that is, 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).
4. **The individual component** reflects the activities in which individuals want to participate and the options they have to fulfil those needs. This directly relates to the Needs-Opportunities-Abilities (NOA) model (Figure 3.1 in Chapter 3). The need to participate in activities depends for example on age, income, educational level and house-

hold situation. Opportunities to travel and participate in activities depend on people's income and travel budget, educational level, having a driving licence, car ownership, etc. People's abilities depend on people's physical and mental capabilities to travel, e.g. being able to drive a car, having digital skills to use a shared bike or car, etc. These characteristics may strongly influence the total aggregate accessibility result. Several studies have shown that, in the case of job accessibility, inclusion of occupational matching strongly affects the resulting accessibility indicators. Pan et al. (2020), for example, show that in automobile-oriented city such as Houston in the United States, job seekers in poverty and relying on public transport have very limited access to blue collar job opportunities.

The four components have a direct influence on accessibility but also an indirect one through interactions between the components. For example, the land-use component (distribution of activities) is an important factor determining travel demand (transport component) and may also introduce time restrictions (temporal component) and influence people's opportunities (individual component). The individual component interacts with all other components: a person's needs and abilities that influence the (valuation of) time, cost and effort of movement, types of relevant activities and the times at which one engages in specific activities.

The four components explained above have been distinguished to measure physical accessibility to spatially distributed activities. Section 9.6 discusses how ICT (e.g. having access to online goods and services) influences the four components of accessibility.

9.4 OPERATIONALIZATION OF ACCESSIBILITY MEASURES

An accessibility measure should ideally take all components and elements within these components into account. In practice, applied accessibility measures focus on one or more components of accessibility, depending on the perspective taken. There are four main types of accessibility measures:

1. **Infrastructure-based accessibility measures** analyze the (observed or simulated) performance or service level of transport infrastructure, such as the length of infrastructure networks, the density of those networks (e.g. kilometre road length per square kilometre), level of congestion and average travel speed on the road network. This type of accessibility measure is typically used in transport planning (for a discussion see Section 9.5). Some of these measures focus only on the supply of infrastructure, while others also use demand factors.
2. **Location-based accessibility measures** analyze accessibility at locations, typically on a macro-level. The measures describe the level of accessibility to spatially distributed activities, such as the number of jobs within 30 minutes' travel time from each origin location. More complex location-based measures explicitly incorporate capacity restrictions of supplied activity characteristics to include competition effects *see* Section 9.8 for two examples.
3. **Person-based accessibility measures** analyze accessibility at the individual level, such as the activities in which an individual can participate at a given time. This type of measure is founded in time geography (Hägerstrand, 1970) that measures limitations on an individual's freedom of action in their environment. This includes the location and duration of

mandatory activities, the time budgets for flexible activities and travel speed allowed by the transport system. For a description of time geography see also Chapter 3, Section 3.6.

4. **Utility-based accessibility measures** analyze the (economic) benefits that people derive from access to the spatially distributed activities. This type of measure has its origin in economic studies, for details see, for example, de Jong et al. (2007). This type of measure is sometimes used in economic appraisals of transport infrastructure investments (Geurs et al., 2010; Beria et al., 2018).

Table 9.1 presents an overview of different types of accessibility measures, applications and examples, with brief comments on the advantages and disadvantages of the measures used. The different accessibility measures focus on different components of accessibility, often ignoring other relevant elements of accessibility.

Table 9.1 Accessibility indicators, applications and examples

Accessibility type	Applications	Examples	Disadvantages and comments
Infrastructure-based accessibility measures:			
Supply-oriented measures – network level	Description and comparison of characteristics of infrastructure supply in a region or country	Length of motorways, density of rail network	Partial measure of accessibility; does not include land-use and individual components of accessibility.
Supply-oriented measures – connectivity of locations to transport networks	Analysis of how well locations are connected to transport networks	Distance to nearest railway station, exit point of a motorway	Partial measure of accessibility; measures are not suited for a comparison of transport modes, taking available opportunities into account.
Supply-oriented measures – network connectivity	Describing network connectivity, expressing how well each node in a network is connected to each adjacent node	Connectivity or centrality of a node relative to the rest of the network	Partial measure of accessibility. It also does not provide plausible results in complex networks with many indirect linkages between nodes.
Demand- and supply-oriented measures	Describing actual quality of performance of infrastructure networks	Actual travel times on the road network	Partial measure of accessibility; does not include land-use and individual components of accessibility.
Location-based accessibility measures:			
Cumulative opportunities	Counts the number of opportunities that can be reached from an original location within a given travel time, distance or cost (fixed costs); or (average or total) time or cost required to access a fixed number of opportunities (fixed opportunities)	Number of jobs within 30 minutes' travel time by car; average travel time or cost to reach 1 million jobs	These measures are relatively undemanding of data and are easy to interpret for researchers and policy makers, as no assumptions are made on a person's perception of transport, land-use and their interaction. The measure is sensitive to travel time changes.

Accessibility type	Applications	Examples	Disadvantages and comments
Potential accessibility measure	Estimates the number of opportunities in destination locations that can be accessed from an original location, weighted by a distance decay function, which describes how more distant opportunities provide diminishing influences	Index of jobs, population or services which can be accessed from an original location	The measure evaluates the combined effect of land-use and transport elements incorporates assumptions on a person's perceptions of transport by using an impedance function. The measure has no meaning in absolute terms (index). The form of the function should be carefully chosen, and the parameters should be estimated using empirical data on travel behaviour in the study area.
Actual accessibility	Estimates total travel distances, times or costs from an original location to all destinations, weighted by the actual number of trips on an original destination location	Analysis of competition between different transport modes	Detailed information of spatial patterns of travel behaviour is needed.
Person-based accessibility measures:			
Space–time approach	The measures analyze accessibility from the viewpoint of individuals, incorporating spatial and temporal constraints	The number of household activity programmes that can be carried out by individuals, given personal and time constraints	Founded in time geography. Measure is theoretically advanced but is very data demanding.
Utility-based accessibility measures:			
Utility of accessibility	The measures estimate the utility or monetary value (when utility is converted into monetary terms)	Logsum accessibility describing the utility of having access to spatially distributed activities	Founded in microeconomic theory. More difficult to communicate to non-experts.

Table 9.2 presents a matrix of the different accessibility measures and components. Infrastructure-based measures do not include a land-use component; that is, they are not sensitive to changes in the spatial distribution of activities if service levels (e.g. travel speed, times or costs) remain constant. The temporal component is explicitly treated in person-based measures and is generally not considered in the other perspectives, or is treated only implicitly, for example by computing peak- and off-peak-hour accessibility levels. Person-based and utility-based measures typically focus on the individual component, analyzing accessibility on an individual level. Location-based measures typically analyze accessibility on a macro-level but focus more on incorporating spatial constraints in the supply of opportunities, usually excluded in the other approaches (see the dark-shaded cells in Table 9.2 – these emphasize the dominant focus of each category of measures).

Table 9.2 Types of accessibility measures and components

Measure	Component			
	Transport	Land-use	Temporal	Individual
Infrastructure-based measures	Travelling speed; vehicle hours lost in congestion		Peak-hour period; 24-hr period	Trip-based stratification, e.g. home-to-work, business
Location-based measures	Travel time and/or costs between locations of activities	Amount and spatial distribution of the demand for and/or supply of opportunities	Travel time and costs may differ, e.g. between hours of the day, between days of the week, or seasons	Stratification of the population (e.g. by income, educational level)
Person-based measures	Travel time between location of activities	Amount and spatial distribution of supplied opportunities	Temporal constraints for activities and time available for activities	Estimated at the individual level
Utility-based measures	Travel costs between locations of activities	Amount and spatial distribution of supplied opportunities	Travel time and costs may differ, e.g. between hours of the day, between days of the week, or seasons	Utility is derived at the individual or homogeneous population group level

Note: Dark grey: primary focus of measures; light grey: non-primary focus.
Source: Geurs and van Wee (2004)

To operationalize accessibility measures, the most suitable type of accessibility measure needs to be chosen (the rows in Table 9.2), and then the various elements within the different components need to be determined (the columns in Table 9.2). A few examples can illustrate this process:

1. In determining travel times between origin and destination locations, one can choose whether or not to weigh the different time components of a trip, such as access and egress times to and from boarding points, in-vehicle travel times, waiting times and so on. Generally speaking, access and egress and waiting time will incur much greater disutility to travellers than in-vehicle time (e.g *see* Schakenbos et al., 2016; see also Chapter 6 of this book). In particular, a comprehensive approach to measuring public transport accessibility introduces a number of complexities, such as access to and from public transport by different modes. For example, Geurs et al. (2016) examined the impacts of bicycle–train integration policies on job accessibility for public transport users, implementing a detailed bicycle network linked to the public transport network, access/egress mode combinations and station specific access and egress penalties by mode and station type derived from a stated choice survey *see* Chapter 6, Section 6.2 for a description of the travel time components in transport impedance.
2. In determining the costs of car trips, one can include only fuel costs, but also total variable costs, including for example parking costs and fixed costs (e.g. depreciation of the car). Several cost elements can also be integrated in a generalized cost function. Koopmans et al. (2013), for example, developed a generalized cost measure for car use to measure

accessibility changes over time in the Netherlands. Their generalized cost measure included fuel costs, travel time, value of travel time and reliability of travel time.

3. Perceived accessibility, as the actual determinant of decisions regarding activity behaviour, may differ from accessibility measurements based on actual spatial data. Perceptions of the land-use, transport and temporal components may for example relate to knowledge of available opportunities, perceived travel times or distances or temporal availability of activities (e.g. opening hours). Objective and perceived factors may differ greatly, e.g. car drivers greatly over-estimate travel time with public transport (e.g *see* van Exel and Rietveld, 2009). Perceptions may also change over time *see* Pot et al. (2021) for a discussion on perceived accessibility.
4. In determining the land-use component, one needs to consider the spatial unit of analysis (e.g. block level, postcode) but also for how many destination opportunities are to be considered, and how these values are to be aggregated. An access measure involving multiple destination types (e.g. jobs, shops, healthcare) can be weighted to produce a single aggregated measure (Levinson and Wu, 2020). Furthermore, one needs to consider if available opportunities have capacity limitations (such as in the case of school locations and healthcare facilities), as a result of which competition exists, and where accessibility measures need to account for differences in the spatial distribution of the demand and supply of these opportunities (see Section 9.8 for a discussion).

9.5 CHOOSING AND USING ACCESSIBILITY MEASURES

In defining and operationalizing accessibility, there is no one best approach because different situations and purposes demand different approaches (Handy and Niemeier, 1997). However, several criteria can be derived to evaluate the usefulness and limitations of accessibility measures for different study purposes *see*, amongst others, Geurs and van Wee (2004). We summarize these criteria here as follows.

9.5.1 Purpose of the Study

This is the starting point of the operationalization process. What is the purpose of the study and, following from that, what is the main reason for analyzing accessibility? All other choices essentially follow on from this. The definition and operationalization would, for example, strongly differ when the study purpose is to evaluate accessibility impacts of a transport project, or to analyze social equity effects, or the economic benefits that people derive from having access to opportunities. This means that the analysis of transport policy can be carried out through more aggregate, location-based accessibility measures, whereas the analysis of social equity effects requires a highly spatially differentiated and disaggregated analysis. The analysis of economic benefits would require choosing a utility-based accessibility measure that is directly linked to microeconomic theory.

In the transport planning practice, there is also a link between the choice of the accessibility measure and policy objectives set in transport policy documents. Since the mid-twentieth century, the fundamental transport policy goal has been to achieve faster vehicle operating speeds. To measure the effectiveness of transport policies to meet that goal, accessibility measures such as delay per capita, vehicle hours or money wasted while waiting in traffic and highway level of service have been used (Levine et al., 2012). These accessibility measures are however not simply after-the-fact assessments, but they are also used proactively to guide policy towards car-based transport investments (Levine et al., 2019). Analysis of over 170 Dutch municipal transport policy documents shows that car-oriented mobility planning and the use of simple infrastructure-based accessibility indicators still dominates Dutch municipal transport planning. Location-based accessibility measures are mostly found in transport policies of a few large cities and highly urban municipalities (Akse et al., 2021).

9.5.2 Scientific Quality

An accessibility measure should ideally take all of the components and elements within these components into account (Section 9.2). Thus an accessibility measure should firstly be sensitive to the changes in the transport and land-use systems and the temporal constraints of opportunities, and it should take individual needs, abilities and opportunities into account. A comprehensive inclusion of all components and their elements implies a level of complexity and detail that can probably never be achieved in practice. However, it is important that the limitations are recognized and described. In the literature, several examples of comparative accessibility studies can be found. Thill and Kim (2010) explored differences between over 70 different location-based accessibility measures and operationalizations. Kwan (1998) and Neutens et al. (2010) explored differences between different location- and person-based accessibility measures. The main conclusion from these studies is that each accessibility measure brings a particular perspective to the measurement of the notion of accessibility that is not fully captured by others. Hence, it is preferable to use multiple accessibility measures and operationalizations in accessibility studies. However, the estimation of multiple accessibility measures requires more effort and it is in conflict with the criterion: operationalization. And it can also be in conflict with the second next criterion, 'Interpretability and communicability', because clients of accessibility research might get confused. The solution may be to estimate multiple accessibility measures, and if the results are highly correlated and not very sensitive to the choices made, to communicate the results of only one measure. If the results differ significantly, this may be communicated as an uncertainty.

9.5.3 Operationalization

The operationalization of accessibility measures is related to the ease with which the measure can be used in practice, for example in ascertaining availability of data, models and techniques, and time and budget. This criterion will usually be in conflict with one or more of the theoretical criteria described above. As noted in Section 9.1, while practitioners typically are convinced that comprehensive accessibility measures are useful in the planning practice, many do not use them in their work. The availability of data, for example, can be an important barrier towards the use of advanced accessibility measures and tools (e.g. software packages) in the planning practice (e.g. Boisjoly and El-Geneidy, 2017). A promising way forward to improve the ease of using accessibility measures is to develop open source, transferable and interactive accessibility tools which have easy-to-use interfaces. The rise of WebGIS-technology allows the development of such tools. Pajares et al. (2021) presents an example of such an attempt, following an iterative software development process in close cooperation with practitioners. The tool was tested and transferred to more than 20 cities in Germany, Colombia and Portugal.

9.5.4 Interpretability and Communicability

Measures of accessibility have evolved with advances in GIS technology and data gathering methods including geocoded spatial data and crowd-sourced, GPS-based travel times (Wu and Levinson, 2020). In academic literature, accessibility studies have developed complex and high resolution accessibility measures, partly in response to the recognition that the aggregate measures lack many important details. However, accessibility measures which are used in the planning practice are typically easy to interpret for researchers and policy makers, such as travel speed on the road network or cumulative opportunity measures, but which have strong methodological disadvantages. It is important that comprehensive approaches to measure accessibility are made practical. Researchers, planners and policy makers should be able to understand and interpret the measure, and communicate results to clients, as otherwise it is not likely to be used in evaluation studies of land-use and/or transport developments or policies and will thus have no impact on the policy making process.

The interpretations of comprehensive accessibility measures can for example be improved by comparing accessibility across place or time, or both place and time, rather than focusing on absolute levels of accessibility. To improve interpretation, accessibility estimations can also be indexed. For example, the base year value or a reference scenario can be indexed at the level of 100. The value of the accessibility indicators could then be indexed and compared to this base level value. Furthermore, location-based accessibility measures by definition capture the combined effects of land-use (distribution of opportunities) and transport impedance (time, cost, etc.) factors. This can make interpretation of accessibility changes difficult. What causes a change in accessibility in an area: a change in travel time or a change in land use? To improve interpretation, the influence of each factor on the overall accessibility change can be shown. An example of such an approach is given by Moya-Gómez and Geurs (2018), who examined the spatial and temporal dynamics in job accessibility by car in the Netherlands during the economic crisis and its aftermath (2009–14) and showed the separate influence of land-use changes and road network investments on the development of (job) accessibility for the Netherlands. Computation of the different components of accessibility facilitates both the explanation of overall accessibility changes and the relative position of regions.

9.6 DIGITAL AND PHYSICAL ACCESSIBILITY

Information and communications technologies (ICTs) are permeating modern lifestyles, shaping and colouring the undertaking of activities and travel (Lyons, 2014). ICTs include personal computer use at fixed locations, mobile devices, such as laptops and smartphones, and infrastructure-related information provision technologies, such as Dynamic Route Information Panels (DRIPS) for roads and public transport travel information. Since the start of the World Wide Web over 30 years ago we have moved into a world where we can search for and engage with almost anything online, whether information, other people, goods or services; and we can do so (if equipped) from (almost) anywhere and anytime – whether at our desks, on the move or in our living rooms (Lyons, 2014). This affects how we travel and access people, goods and services. In contrast to the numerous studies on how various ICTs affect how we travel (e.g *see* for overviews Aguiléra et al., 2012; Lyons, 2014), there are only a few studies on the impacts on accessibility. ICTs can however impact accessibility in various ways. Van Wee et al. (2013) provide a systematic overview of potential impacts of ICT on accessibility, using the four components of accessibility.

ICT can have complex impacts on accessibility as it affects all four of its components:

1. **Transport component**: ICTs can affect travel resistance in many ways. Firstly, a traveller may access (personalized) travel information before and during the trip via individual ICT devices (e.g. PCs, PDAs, smartphone), and as a result reduce access time, and optimize route and mode choice. The development of multi-tasking during journeys (e.g. making phone calls, online working) affects travel resistance. For example, ICTs allow public transport users to use part of their travel time in a useful way and not all travel time should be considered unproductive and 'lost'. Molin et al. (2020) examined the impact of onboard activities on the value of time (VoT) of train users in the Netherlands, and they concluded that VoT due to onboard activities is 30% lower for commuters and almost 50% for leisure travellers. Furthermore, during the COVID-19 pandemic, many governments and companies promoted and facilitated teleworking. In the Netherlands teleworking resulted in significant reductions in car commuting, reducing transport impedance (e.g. lower peak-hour travel times). This might have long-term effects. In the Netherlands, for example, 40% of workers indicated, after one month of teleworking during the lockdown in 2020, that they would like to continue teleworking (one or more days per week) after the pandemic, whereas 23% of workers were teleworking before the pandemic (Olde Kalter et al., 2021).
2. **Land-use component**: ICTs influence which persons carry out which activities at which locations, due to changes in activities or activity locations; e.g. a person deciding to work at home using ICT instead of travelling to work. ICT may directly or indirectly impact the distribution of actors (households, shops, companies, etc.) over the given locations of destinations. An example of a direct impact is that the city of Amsterdam has excellent digital infrastructure and hosts large data-transport hubs which has helped to attract many companies in the information industry. An example of an indirect impact is that the rapid increase in online sales that, particularly during the COVID-19 pandemic, profoundly changes the way consumer goods are bought and sold. Online shopping typically substitutes shopping trips (Le et al., 2021) and changes the spatial distribution of retail businesses. Studies in the UK, for example, show that growth in e-commerce increased the number of vacant shops in particular in (small) town centres and small retail centres. (Dolega and Lord, 2020).
3. **Temporal component**: ICTs affect 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). Thanks to ICT a number of activities can be carried out at non-traditional

times of day (e.g. working at night or on the weekend instead of during office hours). Also, ICTs can allow the traveller to travel more efficiently (e.g. outside rush hours), save time and spend more time on other activities.

4. **Individual component**: ICT can have an impact on the needs (and wants) of people: people might, for example, want to go to a concert they are aware of thanks to ICT. ICT can also have a negative impact on people's abilities to travel. Durand et al. (2021) state that digital technologies are progressively becoming indispensable. In shared mobility 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 digitalization in transport services exists along dimensions of age, income, education, ethnicity, gender and geographical region.

In the literature, some studies developed conceptual frameworks to combine physical and digital accessibility (e.g. Miller, 2005; Lu et al., 2014) but only a few applied these models to real case studies. One example is from Cavallaro and Dianin (2022) who developed a potential job accessibility measure (see also Section 9.8) that combines physical accessibility and teleworking into a single accessibility measure. The study included homeworking costs (such as energy and internet subscriptions) as virtual 'transport' impedance. From an application of the model to a rural and mountainous area in north-western Italy it was concluded that teleworking plays a minor role in the overall job accessibility. This is explained by the partial development of digital infrastructures and low level of teleworking opportunities in that region. In regions or countries with high quality digital infrastructure and high teleworking levels, the impact of teleworking on overall job accessibility can be expected to be much higher.

The overall impact of ICTs on accessibility can be profound. However, there are several gaps in our knowledge on the impacts of ICT on accessibility (see also van Wee et al., 2013). Firstly, it is unknown how the many different interactions between ICT and accessibility components combine overall. For example, research on telecommuting show that telecommuters typically have longer commuting distances due to more remote residential locations (Cerqueira et al., 2020). However, telecommuting can also enable people to achieve a desired but more distant residential location (e.g. bigger home and/or lower housing prices), without a net increase in commute travel. So an interaction exists between residential location, job location and ICT use, but we still poorly understand these interactions. Another example is that the ICT can relax temporal constraints, as consumers no longer depend on the opening times of (physical) shops to buy goods. Thus, an interaction exists between ICT access to shops. However, it is unclear if digital access to shops influences the temporal distribution of activities of persons, and maybe even residential location, and such choices influence the level of accessibility.

Other knowledge gaps relate to, amongst others, the effect of personalized information provision using mobile phone technologies on transport impedances (including comfort of travel) and equity implications of the growing importance of digital accessibility. Over 40% of the EU population still lacks at least basic digital skills and even in the Netherlands, one of the three most digitalized countries in the European Union, about 20% of the working population lack basic digital skills, and these people are generally older, lower educated and more often female (Non et al., 2021). Moreover, digital technologies are progressively becoming indispensable for physical accessibility. Shared mobility services such as ride sourcing, car and bike sharing can often only be used with digital technologies. But we still poorly understand the importance of such developments for accessibility. This relates to the following discussion about the equity of accessibility.

9.7 EQUITY OF ACCESSIBILITY

People, groups of people and regions by definition do not have the same level of access to destinations, such as shops, jobs or medical services. Planners have long been interested in improving the conditions experienced by disadvantaged regions and/or population groups. There is also a large body of research focusing on questions of uneven or inequitable access to places and forms of movement. Early examples use various measures of physical accessibility as a social indicator of the ease with which citizens may reach different employment and services opportunities. Inequalities in accessibility are influenced strongly by the population characteristics of areas as well as by location (Wachs and Kumagai, 1973).

Equity is an important concept but also very difficult to define (van Wee and Mouter, 2021). Transportation equity typically refers to the distribution of transport-related benefits and costs over members of society. Di Ciommo and Shiftan (2017) argue that transportation equity has three key components:

1. the benefits and costs that are being distributed;
2. the population groups over which the benefits and costs are distributed; and
3. the distributive principle that determines whether a particular distribution is 'morally proper' and 'socially acceptable'.

Research on the first two components of transport equity have a long history in transport and urban research. Equity of accessibility is the most assessed aspect in transport policy evaluations (see van Wee and Mouter, 2021, for an overview). There is a large body of literature focusing on questions of uneven or inequitable access to places and forms of movement (e.g. van Wee and Geurs, 2011). Early examples use various measures of physical accessibility as a social indicator of the ease with which citizens can reach different employment and services opportunities (e.g. Wachs and Kumagai, 1973). Equity analysis however is very complex as there are several types of equity (see Thomopoulos et al., 2009, for an overview), various ways to categorize people for equity analysis, numerous impacts to consider and various ways of measuring these impacts (van Wee and Geurs, 2011). In practice, one or more quantitative indicators, such as the Gini index, are often used to express the level of (in)equality of accessibility *see* Chapter 15 for more information on equity measures.

Research on fairness and (distributive) justice (the third component in the list by Di Ciommo and Shiftan, 2017, as presented above) is a fast growing field within transportation research. In particular, recent studies link accessibility approaches to transport justice frameworks based on key theories of justice including Rawls' egalitarianism and the Capability Approaches (CA) (e.g *see* for literature reviews Pereira et al., 2017, and Vecchio and Martens, 2021). Karner et al. (2020) state that transportation justice describes a normative condition in which no person or group is disadvantaged by a lack of access to the opportunities they need to lead a meaningful and dignified life. Several authors have suggested that the Capabilities Approach developed by Amartya Sen and Martha Nussbaum (e.g. Nussbaum and Sen, 1993; Sen, 2009) can provide a conceptual framework to properly appraise the transport system as well as new transport projects. The Capabilities Approach has five key features to understand a person's level of freedom which can be summarized as follows (e.g. Vecchio and Martens, 2021, for more details):

1. Resources: commodities and intangible goods available to a person, which are considered as means to achievement.
2. Capabilities are the freedoms available to a person. Each capability is whatever people are able to do and be in a variety of areas of life.
3. Functionings: what people actually achieve 'to be' or 'to do'. Each person puts into practice (or not) the capabilities available to her. The basic element of an individual's functioning is travelling.
4. Conversion factors: personal, social and environmental conditions that form the individual life experience. The factors determine what possibilities the person has to convert resources into freedoms.
5. Choice refers to the person's decision in favour of a particular 'state' over another, selected from within their capability set.

There is a growing stream of research arguing that accessibility can be understood as a capability within the framework of the Capability Approach. A capability can, as a practical operationalization of this approach, be interpreted as a person's possibility of engaging in a variety of out-of-home activities. Accessibility captures the possibility of each person to actually participate in valued activities. This can involve travel or virtual accessibility (see Section 9.6). This also involves analysis of elements which have not received much attention in the literature so far, such as wellbeing. Vecchio and Martens (2021) argue that the higher a person's accessibility level, the larger the person's freedom to choose to travel to 'the best' opportunities with a substantial positive impact on wellbeing. Even if the person does not always choose that 'best' option, the freedom embodied in a large choice set is in itself likely to enhance wellbeing. It also creates complexity as perceptions of what are minimum levels of access to opportunities differ across people. Furthermore, it has also been argued that transport policy can be seen as a conversion factor to use the Capability Approach in transport policy evaluations (Randal et al., 2020). Transport policy in this perspective can enhance or limit accessibility but also other capabilities such as health and wellbeing. Nahmias-Biran and Shiftan (2019) developed a conceptual framework using a utility-based accessibility measure to translate capabilities into the (monetary) 'Value of Capability Gains' that can be used in cost–benefit analysis. However, the inclusion of capabilities elements in transport policy appraisal tools is quite complex and requires much more exploration.

Furthermore, there is little attention in the literature for the joint analysis of the distribution of advantages and disadvantages of transport (accessibility, air pollution, etc.), their interactions and correlations, and their evolution over time, and resulting equity implications (Geurs et al., 2021). These relationships can be quite complex. For example, da Schio et al. (2019)

found flagrant patterns of inequality in accessibility and air pollution in the Brussels region, but these do not reflect the socio-economic structure of the region.

Finally, some authors argue that to achieve more fair transport planning it is not sufficient to conduct quantitative equity analysis, but also full and fair participation of affected communities in the decision making is needed (Karner and Marcantonio, 2018). To learn more about equity considerations and the newest methods that are used to integrate them in policy appraisal, see Chapter 14.

9.8 APPLICATIONS: TWO EXAMPLES OF ACCESSIBILITY MEASURES

Table 9.1 presented an overview of different types of accessibility measures, applications and examples. In this section we will give two examples of frequently used accessibility measures in the literature: (1) the potential accessibility measure and (2) the Shen accessibility measure. The Shen index takes into account the spatial distribution in the demand for opportunities (competition effects), whereas the potential accessibility measure does not. The application of the two measures illustrates how the choice and operationalization of an accessibility measure may strongly affect the conclusions on accessibility.

9.8.1 Potential Accessibility Measures

Potential accessibility measures (also called gravity-based measures) have been widely used in urban and geographical studies since the late 1940s, including the seminal work of Hansen (1959). The potential accessibility measure estimates the accessibility of opportunities in zone *i* to all other zones *n* in which smaller and/or more distant opportunities provide diminishing influences. The measure has the following form, assuming a negative exponential cost function:

$$A_i = \sum_{j=1}^{n} D_j e^{-\beta c_{ij}} \tag{9.1}$$

where Ai is a measure of accessibility in zone *i* to all opportunities D (e.g. jobs, schools, health facilities) in zone *j*, c_{ij} the impedance or costs of travel between *i* and *j*, and β the cost sensitivity parameter.

The impedance (or distance decay) function makes accessibility decrease if costs increase. The function has a significant influence on the results of the accessibility measure. For plausible results, the form of the function should be carefully chosen, and the parameters of the function should be estimated using recent empirical data of spatial travel behaviour in the study area. Several studies have used different impedance functions, such as negative exponential, power, Gaussian or logistic functions. However, the negative exponential function is the most widely used and the most closely tied to travel behaviour theory.

The standard potential accessibility index calculates the geographic distribution of accessibility between areas or zones of analysis. This does not account for the number of people who potentially access the opportunities. This makes it impossible to compare potential accessibility measures between different case study areas (cities, countries) with different volumes of opportunities. To account for this, potential accessibility can be weighted by the population in each spatial unit or zone @mto estimate person-average accessibility:

$$A_{i\,person} = \frac{A_i}{P_i} \tag{9.2}$$

where $A_{i\,person}$ is the accessibility in zone i per person (by mode); P_i is the population in zone i.

Potential measures have the practical advantage that they can be easily computed using existing land-use and transport data (and/or models), and they have been traditionally employed as an input for estimating infrastructure-based measures. A potential measure is however not so easy to interpret, as it combines land-use and transport elements and weighs opportunities according to the impedance function. Moreover, in practice potential accessibility measures (and other location-based measures) are typically measured for a particular place, mode, purpose and time in a particular year. Levinson and Wu (2020) argue that more generalized measures of (potential) accessibility are needed that ideally would be measured for all places, all modes, all purposes, at all times. In case the measure is used in transport project evaluation, it ideally is also measured over the lifecycle of a project.

9.8.2 Shen Accessibility Measure

Standard potential accessibility measures ignore the spatial distribution in the demand for opportunities, i.e. the so-called competition effects. For example, the workers compete for jobs; firms compete for workers in the labour force. Ignoring such effects could lead to misleading conclusions. This is illustrated in Figure 9.2. A potential accessibility indicator would estimate (left side) that jobs in location j_4 are the most accessible (closest by). However, accounting for

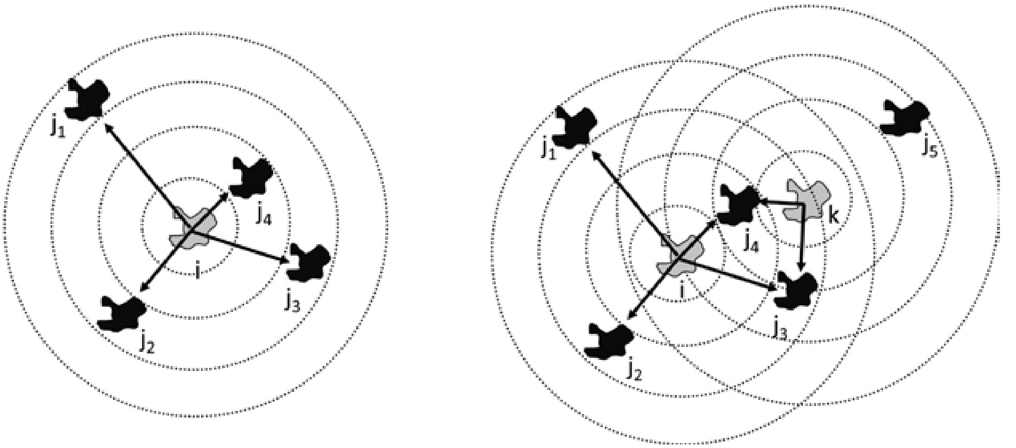


Figure 9.2 Visualization of potential accessibility (left) and Shen measure (right)

competition with persons in location *k* means jobs in location j_2 are more accessible, as opportunities in locations j_3 and j_4 are within reach of competitors in location *k*.
To incorporate competition effects, several authors have adapted potential accessibility measures. A relatively simple approach has been to measure accessibility to certain opportunities (jobs) and to individuals (workers) from a given location and then divide one measure by the other (Levinson, 1998; van Wee et al., 2001). This approach is useful if the travel distance between origins and destinations is relatively small, such as for elementary schools. A more advanced approach developed by Shen (1998) involves incorporating the demand potential (job seekers) to the calculation by dividing the supply (jobs) located in destination zone *j* by the demand potential within reach of that zone *j*. This approach is also called the two-step floating catchment area method which is frequently used in studies examining (spatial inequalities in) accessibility of healthcare services (see for an overview see Chen and Jia, 2019). Figure 9.2 visualizes the difference between a standard potential accessibility measure and the Shen index. The Shen index (S_i) has the following functional form:

$$S_i = \sum_j \frac{O_j \bullet f(t_{ij})^{\bullet}}{D_j}, \quad D_j = \sum_k P_k \bullet f(t_{kj}) \qquad (9.3)$$

where S_i is the accessibility in zone *i* (by mode) while considering competition from other zones *k* by users (of a specific mode); P_k is the population in location *k*; $f(t_{kj})$ is the impedance as a function of the travel time t_{kj} between *k* and *j* using a specific mode. Figure 9.2 illustrates the effect of competition. The Shen index (Equation 9.3) accounts for the competition using only the selected mode of travel, e.g. for car only competition between car commuters are included. This is a simplification. Pritchard et al. (2019) developed a multi-modal Shen index (Equation 9.4). The denominator, which accounts for population, uses the fastest travel time alternative $t_{kj}^{m_f}$between each origin–destination (O–D) pair (i.e. the greatest possible competition from each zone *k* to any zone *j*). This means that if the travel time by car is faster than, for example, public transport from zone *k* to *j* then the travel time by car is selected for this O–D pair. This is a good indicator because like potential accessibility it focuses on the supply side of accessibility and does not assess the modal choice of individual residents; the greatest potential competition from any area *k* is considered.

$$S_i^{m_x} = \sum_j \frac{O_j \bullet f\left(t_{ij}^{m_x}\right)^{\bullet}}{D_j^{fastest}}, \quad D_j^{fastest} = \sum_k P_k \bullet f\left(t_{kj}^{m_f}\right) \qquad (9.4)$$

where: $S_{i\,MM}^{m_x}$ is the accessibility in zone i by mode x with competition from any mode; $f\left(t_{kj}^{m_f}\right)$ is the impedance as a function of the fastest travel time by any mode between *k* and *j*.

In the literature, more advanced approaches are used to include competition effects. The Shen index simplifies competition effects, which can be illustrated using Figure 9.2. The Shen index does not include job opportunities in location j_5 within reach of workers in location *k* but outside reach of workers living in location *i*. To allow for these effects, iterative procedures are needed, incorporating the competition on supplied opportunities and the competition on demand (e.g. Geurs and Ritsema van Eck, 2003; El-Geneidy and Levinson, 2011).

An application of the potential accessibility and Shen accessibility measures is presented by Pritchard et al. (2019). They conducted a comparative accessibility study, and estimated job accessibility for car and public transport in Greater London, São Paulo and the Dutch Randstad region, the most populated area in the west of the Netherlands. Pritchard et al. (2019) estimated two types of potential accessibility measures (zonal and person based; Table 9.3) and two types of Shen measures (intra-modal and multi-modal; Table 9.3). The results can be found in Table 9.3. The car provides, on average, higher zonal potential accessibility to the residents of all three city-regions. The standard potential accessibility measure indicates that residents in São Paulo are the best off, having the highest average accessibility by car and transit, and Londoners having the lowest. However, the city-regions have different total volumes of opportunities and working-age population, with São Paulo having the most jobs but also workers (4.7 and 7.8 million, respectively) and the Randstad area having the least jobs and also the smallest working-age population (3.6 and 5.3 million, respectively). This changes the ranking of cities; the car provides access to more jobs per resident in London than São Paulo and the Randstad area. Incorporating job competition has a stronger effect on the conclusion. The mode-specific Shen index shows that workers in the Randstad area are the best off – they have access to 0.8 jobs per worker – whereas in São Paulo this is about 0.6. However, the position of public transport users changes radically if competition with car drivers is included as competitors. Dutch public transport users are worse off – the accessible number of jobs per worker drops from 0.8 to 0.1 jobs per worker. Thus, the choice and operationalization of accessibility measures affect the results and conclusions of accessibility studies.

Table 9.3 Job accessibility in the Randstad area, Greater London and São Paulo based on different operationalizations of potential and Shen accessibility measures (Pritchard et al., 2019)

			Car	Public transport
São Paulo	Potential Accessibility	Standard	2,166,153	638,993
		Person-Averaged	409	144
	Shen Accessibility	Mode-Specific	0.62	0.58
		Best-Alternative	0.62	0.18
London	Potential Accessibility	Standard	786,490	179,334
		Person-Averaged	477	116
	Shen Accessibility	Mode-Specific	0.70	0.71
		Best-Alternative	0.70	0.15
Randstad	Potential Accessibility	Standard	1,585,952	202,858
		Person-Averaged	355	37
	Shen Accessibility	Mode-Specific	0.81	0.76
		Best-Alternative	0.81	0.09

9.9 CONCLUSIONS

This chapter has provided an overview of different perspectives, components and operationalizations of accessibility, together with applications of accessibility measures. Furthermore, new research areas related to the impact of ICTs on accessibility and measurement of equity in accessibility are described. The main conclusions are as follows.

It is very important to make careful decisions on the definition and operationalization of accessibility, as the output is dependent on the definition and the choice of accessibility measure. The four criteria on which decisions can be based are (1) purpose of the study, (2) scientific quality, (3) operationalization (cost, effort) and (4) interpretation and communication.

In practice, the accessibility measures used are often those that are easy to operationalize and interpret, rather than those that satisfy more stringent theoretical criteria. Applying a full set of scientific quality criteria would imply a level of complexity and detail that is difficult to achieve in practice. This means that different situations and study purposes demand different approaches. However, it is important to recognize the implications of ignoring one or more of these criteria.

Location- and utility-based accessibility measures can be considered effective measures of accessibility, which can also be used as input for social and economic evaluations. These measures overcome the most important shortcomings of infrastructure-based measures and can be computed with state-of-the-practice land-use and transport data and models.

Equity analysis of accessibility is increasingly becoming important in transport planning. Equity analysis is however not straightforward. There are several types of equity, various ways to categorize people for equity analysis, numerous impacts to consider and various ways of measuring these impacts. Dealing with fairness and justice in transportation requires a more complete understanding of accessibility than traditional approaches have been able to deliver to date.

ICTs affect how we travel and access people, goods and services. The COVID-19 pandemic has amplified this affect. ICTs affect all four components of accessibility, and their interactions. There is relatively little research combining physical and digital accessibility in accessibility measures. Moreover, there are many gaps in our knowledge on the possible impacts of ICT on the different components of accessibility, and the equity implications of the growing importance of digital accessibility for physical accessibility. Shared mobility services for example can often only be accessed using digital technologies.

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