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Accessibility evaluation of land-use and transport strategies: review and research directions

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Abstract

A review of accessibility measures is presented for assessing the usability of these measures in evaluations of land-use and transport strategies and developments. Accessibility measures are reviewed using a broad range of relevant criteria, including theoretical basis, interpretability and communicability, and data requirements of the measures. Accessibility impacts of land-use and transport strategies are often evaluated using accessibility measures, which researchers and policy makers can easily operationalise and interpret, such as travelling speed, but which generally do not satisfy theoretical criteria. More complex and disaggregated accessibility measures, however, increase complexity and the effort for calculations and the difficulty of interpretation. The current practice can be much improved by operationalising more advanced location-based and utility-based accessibility measures that are still relatively easy to interpret for researchers and policy makers, and can be computed with state-of-the-practice data and/or land-use and transport models. Research directions towards theoretically more advanced accessibility measures point towards the inclusion of individual's spatial–temporal constraints and feedback mechanisms between accessibility, land-use and travel behaviour. Furthermore, there is a need for theoretical and empirical research on relationships between accessibility, option values and non-user benefits, and the measurement of different components of accessibility.

Keywords: Accessibility; Land-use; Transport; Policy evaluation

1. Introduction

Accessibility, a concept used in a number of scientific fields such as transport planning, urban planning and geography, plays an important role in policy making. However, accessibility is often a misunderstood, poorly defined and poorly measured construct. Indeed, finding an operational and theoretically sound concept of accessibility is quite difficult and complex. As a result, land-use and infrastructure policy plans are often evaluated with accessibility measures which are easy to interpret for researchers and policy makers, such as congestion levels or travel speed on the road network, but which have strong methodological disadvantages. This paper presents a thorough review of accessibility studies and research directions to improve the current practice of land-use and transport policy appraisal. Several authors have written review articles on accessibility measures, often focusing on certain perspectives, such as location accessibility (e.g. Song, 1996; Handy and Niemeier, 1997), individual accessibility (e.g. Pirie, 1979; Kwan, 1998) or economic benefits of accessibility (e.g. Koenig, 1980; Niemeier, 1997). Our review differs from existing review articles in the following ways. Firstly, accessibility measures are reviewed from different perspectives, and we do not focus on one specific perspective. The main purpose is to assess the usability of accessibility measures in evaluations of both land-use and transport changes, and related social and economic impacts. Secondly, measures are reviewed according to a broad range of relevant criteria, i.e. (a) theoretical basis, (b) interpretability and communicability, (c) data requirements and (d) usability in social and economic evaluations. This review, based on an extensive literature study (Geurs and Ritsema van Eck, 2001), will approach the different perspectives and components of accessibility in Section 2, the accessibility measures in Section 3 and explore the conclusions in Section 4. Future research paths will be outlined in Section 5.

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2. Accessibility measures: perspectives and components

Accessibility is defined and operationalised in several ways, and thus has taken on a variety of meanings. These include such well-known definitions as 'the potential of opportunities for interaction' (Hansen, 1959), 'the ease with which any land-use activity can be reached from a location using a particular transport system' (Dalvi and Martin, 1976), 'the freedom of individuals to decide whether or not to participate in different activities' (Burns, 1979) and 'the benefits provided by a transportation/land-use system' (Ben-Akiva and Lerman, 1979). In our study, accessibility measures are seen as indicators for the impact of land-use and transport developments and policy plans on the functioning of the society in general. This means that accessibility should relate to the role of the land-use and transport systems in society, which, in our opinion, will give individuals or groups of individuals the opportunity to participate in activities in different locations. Focusing on passenger transport, we define 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). Furthermore, the terms 'access' and 'accessibility' in the literature are often used indiscriminately. Here, access is used when talking about a person's perspective, accessibility when using a location's perspective.

A number of components of accessibility can be identified from the different definitions and practical measures of accessibility that are theoretically important in measuring accessibility. Four types of components can be identified: land-use, transportation, temporal and individual.

1. The *land-use component* reflects the land-use system, consisting of (a) the amount, quality and spatial distribution opportunities supplied at each destination (jobs, shops, health, social and recreational facilities, etc.), and (b) the demand for these opportunities at origin locations (e.g. where inhabitants live), (c) the confrontation of supply of and demand for opportunities, which may result in competition for activities with restricted capacity such as job and school vacancies and hospital beds.
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; included are 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.
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).
4. The *individual component* 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. These characteristics influence a person's level of access to transport modes (e.g. being able to drive and borrow/use a car) and spatially distributed opportunities (e.g. have the skills or education to qualify for jobs near their residential area), and may strongly influence the total aggregate accessibility result. Several studies (e.g. Cervero et al., 1997; Shen, 1998; Geurs and Ritsema van Eck, 2003) have shown that in the case of job accessibility, inclusion of occupational matching strongly affects the resulting accessibility indicators.

Fig. 1 shows the relationships between these components and accessibility (as defined above), and relationships between the components themselves: here, 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 in which one engages in specific activities. Furthermore, accessibility may also influence the components through feedback mechanisms: i.e. accessibility as a location factor for inhabitants and firms (relationship with land-use component) influences travel demand (transport component), people's economic and social opportunities (individual component) and the time needed to carry out activities (temporal component).

Following our definition of accessibility, 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. Four basic perspectives on measuring accessibility can be identified.

1. *Infrastructure-based* measures, analysing the (observed or simulated) performance or service level of transport infrastructure, such as 'level of congestion' and 'average travel speed on the road network'. This measure type is typically used in transport planning.

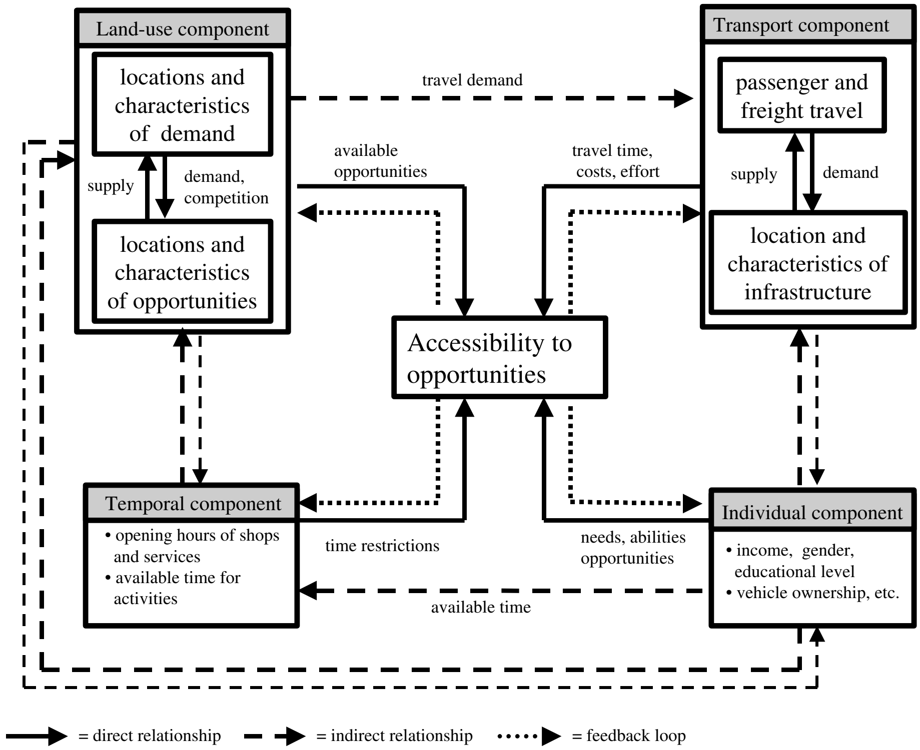

Fig. 1. Relationships between components of accessibility.

2. *Location-based* measures, analysing 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 min travel time from origin locations'. More complex location-based measures explicitly incorporate capacity restrictions of supplied activity characteristics to include competition effects. Location-based measures are typically used in urban planning and geographical studies.
3. *Person-based* measures, analysing 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 the space–time geography of Hägerstrand (1970) that measures limitations on an individual's freedom of action in the environment, i.e. the location and duration of mandatory activities, the time budgets for flexible activities and travel speed allowed by the transport system.
4. *Utility-based* measures, analysing the (economic) benefits that people derive from access to the spatially distributed activities. This type of measure has its origin in economic studies.

Table 1 presents a matrix of perspectives on accessibility and components. The table shows each perspective

Table 1
Perspectives on accessibility and components

Measure	Component			
	Transport component	Land-use component	Temporal component	Individual component
Infrastructure-based measures	Travelling speed; vehicle-hours lost in congestion		Peak-hour period; 24-h 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 locations of activities	Amount and spatial distribution of supplied opportunities	Temporal constraints for activities and time available for activities	Accessibility is analysed at 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

to focus on a certain component, ignoring other relevant elements of accessibility. Infrastructure-based measures do not include a land-use component; i.e. 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 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, analysing accessibility on an individual level. Location-based measures typically analyse accessibility on a macro-level, but focus more on incorporating spatial constraints in the supply of opportunities, usually excluded in the other approaches.

3. Review of accessibility measures

3.1. Criteria for accessibility measures

This section reviews the different types of accessibility measures according to relevant criteria. Although there is no best approach for accessibility because different situations and purposes demand different approaches (Handy and Niemeier, 1997), several criteria can be derived to evaluate the usefulness and limitations of accessibility measures for different study purposes. Such criteria can for example be found in Black and Conroy (1977), Jones (1981) and Handy and Niemeier (1997). Here, we use criteria from the perspective or our definition of accessibility and the usefulness of the concept of accessibility in evaluations of land-use and transport changes. Our criteria are: (1) theoretical basis, (2) operationalisation, (3) interpretability and communicability, and (4) usability in social and economic evaluations. The criteria are described in short below.

3.1.1. Theoretical basis

An accessibility measure should ideally take all components and elements within these components into account (see Section 2). Thus, an accessibility measure should firstly be sensitive to changes in the transport system, i.e. the ease or disutility for an individual to cover the distance between an origin and a destination with a specific transport mode, including the amount of time, costs and effort. Secondly, an accessibility measure should be sensitive to changes in the land-use system, i.e. the amount, quality and spatial distribution of supplied opportunities, and the spatial distribution of the demand for those opportunities, and the confrontation between demand and supply (competition effects). Accessibility measures which do not account for competition effects may lead to inaccurate or even misleading results (Shen, 1998). Note that land-use changes not only have a direct impact on accessibility but also an indirect impact, via the transport system. E.g. more urbanisation in a densely populated area might increase congestion levels, and so the disutility of travel. This impact is expressed via the transport component. Thirdly, a measure should be sensitive to temporal constraints of opportunities. Finally, a measure should take individual needs, abilities and opportunities into account. In addition, from these general criteria the following five criteria can be derived according to which an accessibility measure should behave, keeping all other conditions constant:

1. If the service level (travel time, costs, effort) of any transport mode in an area increases (decreases), accessibility should increase (decrease) to any activity in that area, or from any point within that area.
2. If the number of opportunities for an activity increases (decreases) anywhere, accessibility to that activity should increase (decrease) from any place.
3. If the demand for opportunities for an activity with certain capacity restrictions increases (decreases), accessibility to that activity should decrease (increase).
4. An increase of the number of opportunities for an activity at any location should not alter the accessibility to that activity for an individual (or groups of individuals) not able to participate in that activity given the time budget.
5. Improvements in one transport mode or an increase of the number of opportunities for an activity should not alter the accessibility to any individual (or groups of individuals) with insufficient abilities or capacities (e.g. drivers licence, education level) to use that mode or participate in that activity.

These criteria should not be regarded as absolute but more in the line of what accessibility studies should strive for. Applying the full set of criteria would imply a level of complexity and detail that can probably never be achieved in practice. However, it is important that the implications of violating one or more of theoretical criteria should be recognised and described.

3.1.2. Operationalisation

This is 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.

3.1.3. Interpretability and communicability

Researchers, planners and policy makers should be able to understand and interpret the measure, 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. However, Pirie (1981) clearly points out that there is no guaranteed or easy transition from accessibility research to the formulation of public policy and its implementation; public policy on accessibility will only be forthcoming if accessibility is a well-politicised issue.

3.1.4. Accessibility as a social indicator

In general, social impacts of land-use and transport changes (e.g. due to investments) for individuals or societal groups may be very diverse, e.g. changes in visual quality, health impacts and social cohesion within societies. These can be studied using several methods and techniques (e.g. DfT, 2000; Forckenbrock and Weisbrod, 2001). Accessibility measures can be used as a social indicator if they show the availability of social and economic opportunities for individuals (or groups of individuals), i.e. the level of access to essential sources for human existence such as jobs, food, health and social services, along with the potential for social interaction with family and friends. Furthermore, social equity impacts, typically analysed in social impact assessments, can be evaluated if the accessibility measure is spatially differentiated and disaggregated. Obviously, the measure used in social evaluations should satisfy the theoretical criteria described above, especially the individual component of accessibility.

3.1.5. Accessibility as an economic indicator

Economic impacts of land-use and transport projects are also potentially diverse. Economic impacts are usually grouped into (a) direct economic benefits, that is the economic costs and benefits directly related to a project, where travel-cost savings are typically the most important (user) benefit category for infrastructure projects, and (b) indirect economic benefits, the (wider) economic effects not directly related to the project but resulting from the direct impacts, e.g. productivity gains of firms and distributional effects.

Two basic approaches can be identified from the literature on the economy to measure these benefits: (i) micro-economic methods to analyse the direct economic impacts, and (ii) macro-economic methods for the analysis of the 'wider' economic effects. Two classical economic benefit measures from micro-economic welfare theory are typically used to analyse the direct economic impacts in cost-benefit analysis: (a) Marshallian consumer surplus (i.e. consumers' willingness to pay above the prevailing market price) and (b) the more exact Hicksian compensation variation (i.e. the income transfer required to maintain the same utility level). To analyse the wider economic effects, the production function approach based on macro-economic theories is traditionally used with GDP as an economic benefit measure (see for overviews, Banister and Berechman, 2000; Rietveld and Bruinsma, 1998). In general, an accessibility measure may be used as an economic benefit indicator if it can be directly linked to economic theory, or may serve as input for the calculation of economic benefits of land-use/transport changes.

The following sections will review infrastructure-based, location-based, person-based and utility-based measures according to the criteria described above. The review focuses on the question of components being included in the accessibility measures. The question whether the components are incorporated in a theoretically correct way is beyond the scope of this article (see Section 5.5). Table 2 presents the review, showing the positive and negative scores for characteristics of the approaches and measures.

3.2. Infrastructure-based accessibility measures

Infrastructure-based accessibility measures play an important role in current transport policies in many countries, for example, in European countries (Ypma, 2000) and the United States (e.g. see Ewing, 1993). Several measures are used to describe the functioning of the transport system, such as travel times, congestion and operating speed on the road network. For example, policy options from the Dutch National Transport Policy Plan were evaluated with a national transport model using travelling speed as an accessibility measure (AVV, 2000). The UK Transport 2010 policy plan (DETR, 2000) was evaluated using congestion and total time lost in congestion as accessibility measures. Obviously, the advantages of this type of accessibility measure are related to the criteria of operationalisation and communicability; the necessary data and (transport) models are often readily available and measures are easy to interpret for researchers and policy makers. However, this measure type does not satisfy most of the theoretical criteria. The most important is that the measures do not incorporate the land-use component, and are not very capable of treating temporal constraints and individual characteristics. This may strongly affect the conclusions on accessibility. For example, Linneker and Spence (1992) illustrated that inner London has the highest access costs (in terms of time and vehicle operation costs) in the UK, but the highest level of potential accessibility to jobs, despite the high travel cost.

Infrastructure-based measures have important shortcomings for accessibility, social and economic evaluations of land-use and transport changes, as the result of the exclusion of the land-use component. Firstly, infrastructure-based measures ignore potential land-use impacts of transport strategies, for example the impact of improved travelling speed on urban sprawl. Secondly, infrastructure measures do not correctly measure accessibility impacts of land-use strategies, which affect the spatial distribution of activities. Although the indirect impact of land-use changes via speed on the road

Table 2
Summary of review of accessibility measures

Accessibility measure	Examples of applications	Components[a]					Operation-alisation[b]	Interpretation[b]	Usability for evaluation[c]	
		Transport	Land-use		Temporal	Individual			Economic impacts	Social impacts
			Demand	Supply						
Infrastructure-based measures	Linneker and Spence (1992), AVV (2000), DETR (2000)	±	–	–	±	–	+	+	±	–
Location-based measures										
• Contour measure	Ingram (1971), Wickstrom (1971), Wachs and Kumagai (1973); Black and Conroy (1977), Guy (1983)	±	±	–	±	–	+	+	–	–
• Potential measure	Stewart (1947), Hansen (1959), Vickerman (1974); Linneker and Spence (1992), Handy (1994)	+	+	–	±	±	+	±	±	+
• Adapted potential measures	Weibull (1976), Shen (1998), Knox (1978); Joseph and Bantock (1982), Van Wee et al. (2001)	+	+	+	±	±	+	±	±	+
• Balancing factors	Wilson (1970, 1971), Geurs and Ritsema van Eck (2001, 2003)	+	+	+	±	±	+	±	±	+
Person-based measures	Miller (1991), Kwan (1998), Recker et al. (2001)	+	+	–	+	+	–	–	–	+
Utility-based measures										
• Logsum benefit measure	Koenig (1980), Sweet (1997), Niemeier (1997); Handy and Niemeier (1997)	+	+	–	–	±	+	±	+	+
• Space–time measure	Miller (1999)	+	+	–	+	+	–	±	+	+
• Balancing factor benefit measure	Martínez (1995), Martínez and Araya (2000)	+	+	+	–	±	+	±	+	+

[a] Score: + = criterion satisfied; – = not satisfied; ± = partly satisfied.
[b] Score: + = easy to operationalise or interpret; – = difficult; ± = moderately difficult.
[c] Score: + = usable as indicator; – = not usable; ± = (potentially) usable as input for computations.

network (e.g. more congestion) may be included and expressed in these measures, generally speaking and far more important, the direct effect is not. Both shortcomings limit their use as input for economic appraisal studies. In conventional transport project appraisals, access or travel costs are used as input for the well-known rule-of-half measure of consumer surplus (Tressider et al., 1968), estimating the full benefit (difference in costs) obtained by original travellers for origin–destination combinations and half the benefit obtained by new travellers or generated traffic. However, it has been repeatedly being pointed out that this method of appraisal of accessibility benefits is incorrect if the patterns of land-use are forecast to change as a result of the strategy (Neuburger, 1971; Williams (1976); DfT, 2000).

3.3. Location-based accessibility measures

Several types of location-based measures are used in accessibility studies. The distinguishable groups of measures are distance and contour, along with potential measures and the balancing factors of spatial interaction models.

Distance measures (also called connectivity measures) are the simplest class of location-based accessibility measures, e.g. the 'relative accessibility' measures developed by Ingram (1971). Relative accessibility is defined as the degree to which two places or points on the same surface are connected. The simplest measure of relative accessibility is the straight line between two points, but infrastructure-based accessibility measures (average travel times, average speed) between two locations can also be a measure of relative accessibility. Distance measures are often used in land-use planning as standards for the maximum travel time or distance to a given location or to transport infrastructure. If more than two possible destinations are analysed, a *contour measure* is derived (Ingram uses the term 'integral accessibility'). A contour measure, also known as isochronic measure, cumulative opportunities, proximity count or daily accessibility, counts the number of opportunities which can be reached within a given travel time, distance or cost (fixed costs), or measure of the (average or total) time or cost required to access a fixed number of opportunities (fixed opportunities). This measure is popular in urban planning and geographical studies (e.g. Wickstrom, 1971; Wachs and Kumagai, 1973; Gutiérrez and Urbano, 1996; Bruinsma and Rietveld, 1998).

The advantages of distance and contour measures are related to the operationalisation, interpretability and communicability criteria. 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. However, the distance and contour measures clearly do not satisfy most of the theoretical criteria. Firstly, the measures include elements from the land-use and transport component, but fail to evaluate their combined effect. Secondly, the measures do not take competition effects into account, i.e. the spatial distribution of the demand for an opportunity and possible capacity restrictions of provided opportunities (e.g. for jobs, schools, hospitals). Thirdly, the measures do not take individuals' perceptions and preferences into account, i.e. the measure implies that all opportunities are equally desirable, regardless of the time spent on travelling or the type of opportunity. This creates the well-known problems of the arbitrary selection of the isochrone (or isodistance) of interest and the lack of differentiation between opportunities adjacent to the origin and those just within the isochrone of interest (Vickerman, 1974; Ben-Akiva and Lerman, 1979). As a result, applications in evaluations of land-use and transport changes show that the measure is extremely sensitive to travel time changes and are therefore not very capable of explaining accessibility developments in time (Geurs and Ritsema van Eck, 2001). Thus the measures are not very useful as input in social and economic evaluations of land-use and transport changes.

Potential accessibility measures (also called gravity-based measures) have been widely used in urban and geographical studies since the late 1940s; well-known studies are from Stewart (1947), Hansen (1959), Ingram (1971) and Vickerman (1974). 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:

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

where A_i is a measure of accessibility in zone i to all opportunities D in zone j, c_{ij} the costs of travel between i and j, and β the cost sensitivity parameter. The cost sensitivity function used 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 use different impedance functions, such as power, Gaussian or logistic functions; however, the negative exponential function is the most often used and also the most closely tied to travel behaviour theory (Handy and Niemeier, 1997). The potential measure overcomes some of the theoretical shortcomings of the contour measure: the measure evaluates the combined effect of land-use and transport elements, and incorporates assumptions on a person's perceptions of transport by using a distance decay function. The measures are appropriate as social indicators for analysing the level of access to social and economic opportunities for different socio-economic groups. Potential measures have the practical advantage that they can be easily computed using existing land-use and transport data, and/or models, traditionally employed as input for estimating infrastructure-based measures. Potential measures may also be used as input for spatial-economic evaluations of transport projects, for example, Fürst et al. (2000). These authors include population potentials in the production functions as explanatory variables for regional GDP, and evaluate the long-term impacts of European transport infrastructure investments on regional economic growth in the European Union. Disadvantages of potential measures are related to more difficult interpretation and communicability; the measure is not easily interpreted and communicated as it combines land-use and transport elements, and weighs opportunities (according to the cost sensitivity function). Theoretical shortcomings are related to the exclusion of competition effects and temporal constraints (see Section 2).

To incorporate competition effects, several authors have adapted potential accessibility measures. Here, we summarise in short the different approaches. A more detailed description is presented elsewhere (Geurs and Ritsema van Eck, 2003). Firstly, a number of authors tried to incorporate the effects of competition on opportunities in accessibility measures by dividing the opportunities within reach from origin zone i (the 'supply' potential) by a demand potential from zone i, see, for example, Weibull (1976), Knox (1978) and 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 second approach is to use the quotient of opportunities within reach from origin i (supply potential) and potential demand of those opportunities from each destination j, e.g. Breheny (1978), Joseph and Bantock (1982) and Shen (1998). This approach is useful for the analysis of accessibility to destinations where competition effects occur on destination locations (e.g. nature areas) or where available opportunities have capacity limitations (e.g. in the analysis of recreational or health-care facilities). A third, and final, approach is based on the *balancing factors* of Wilson's double constrained spatial interaction model (Wilson, 1970, 1971). The balancing factor a_i and b_j ensure that the magnitude of flow (e.g. trips) originating at zone i and destined at zone j equals the number of activity in zones i (e.g. workers) and j (e.g. jobs). The balancing factors of this model can be interpreted as accessibility measures, modified to account for competition effects (Williams and Senior, 1978). The balancing factors have the following form, assuming the usual negative exponential demand function:

$$a_i = \sum_{j=1}^{n} \frac{1}{b_j} D_j \mathrm{e}^{-\beta c_{ij}} \qquad (2)$$

$$b_j = \sum_{i=1}^{m} \frac{1}{a_i} O_i \mathrm{e}^{-\beta c_{ij}} \qquad (3)$$

The balancing factors are mutually dependent, so they have to be estimated iteratively. As the balancing factors are dependent and estimated in an iterative procedure, they incorporate the competition on supplied opportunities and the competition on demand. Thus, the balancing factors are useful in analysing accessibility for opportunities where competition effects occur on both the origin and destination location, such as job accessibility, where workers compete with each other for jobs and employers compete with each other for employees. An advantage of the measure is the operationalisation; it can be computed using state-of-the-practice land-use models and transport demand models. The disadvantage of the measure are the interpretability and communicability: the measure is relatively complex as it is the result of an iterative process, incorporating both the locations of demand and supply weighted by a distance decay function. Furthermore, the measure is more difficult to estimate because it requires an iterative estimation procedure. These may be reasons why the measure is used relatively seldom as an accessibility measure.

3.4. Person-based accessibility measures

Person-based accessibility measures are founded in the space–time geography of Hägerstrand (1970). The measures analyse accessibility from the viewpoint of individuals incorporating spatial and temporal constraints, i.e. whether and how observed or assuming individual or household activity programmes can be carried out given time restrictions using space–time prisms to describe the travelling patterns in space and time. These space–time prisms can be regarded as accessibility measures, i.e. they give the potential areas of opportunities that can be reached given predefined time constraints. Although space–time approaches seem to have a fast growing interest in travel behaviour research (see Bhat and Koppelman, 1999; Ettema and Timmermans, 1997, for overviews), their application in accessibility studies is relatively rare. Recent applications are taken from Miller (1991, 1999), Dijst and Vidakovic (1997), Kwan (1998) and Recker et al. (2001).

Person-based measures have great theoretical advantages: they satisfy almost all theoretical criteria as a result of the disaggregate approach taken. Kwan (1998) demonstrates that space–time-based measures capture activity-based contextual effects which are not incorporated in traditional location-based accessibility measures; this allows more sensitive assessment of individual variations in accessibility, including gender and ethnic differences. A remaining theoretical shortcoming is that up to now person-based approaches do not account for competition effects; the measures are demand-oriented and do not include potential capacity constraints of supplied opportunities (e.g. available hospital beds, job vacancies). Clearly, this makes the measures less suitable for analysis of job accessibility or other opportunities where competition effects occur. However, the strongest disadvantages are related to operationalisation and communicability. Despite advances in GIS and spatial modelling, operationalisation of person-based accessibility measures still faces many difficulties, including the detailed individual activity–travel data required, their computational intensity and the lack of feasible operational algorithms (Kwan, 1998). An important application difficulty is that necessary data on an individual's time budgets are often not available from standard travel surveys (Thill and Horowitz, 1997). The applications are often restricted to a relatively small region and subset of the population because of the large data requirements. As a result, the results are difficult to aggregate to evaluate accessibility to population groups and/or to a higher geographical scale.

Person-based accessibility measures are potentially very useful for social evaluations of land-use and/or transport changes, as individual characteristics and constraints are accounted for. Furthermore, Miller (1999) reconciles the person-based and utility-based approaches by deriving space–time accessibility and benefit measures founded in micro-economic theory, which opens up the possibility of using person-based accessibility measures in economic evaluations. However, an important shortcoming for the evaluation of land-use and transport investments is that current state-of-the-art activity-based models focus on short-term behavioural responses, simulating daily household activity and travel patterns. To date, no disaggregate behavioural framework has been developed to link long-term land-use changes (e.g. choices of housing and job location) with daily household activity and travel patterns (Waddell, 2001).

3.5. Utility-based accessibility measures

Utility-based accessibility measures interpret accessibility as the outcome of a set of transport choices. Utility theory addresses the decision to purchase one discrete item from a set of potential choices, all of which satisfy essentially the same need, and can be used to model travel behaviour and the (net) benefits of different users of a transport system. Two types of utility-based measures are used in the literature. An initial approach is based on random utility theory using the denominator of the multinomial logit model, also known as the logsum, as an accessibility measure. The logsum serves as a summary measure, indicating the desirability of the full choice set (Ben-Akiva and Lerman, 1985):

$$A_i = \ln\left(\sum_{k=1}^{m} \mathrm{e}^{V_k}\right); \tag{4}$$

$$A_i = -\frac{1}{\lambda}\ln\left(\sum_{k=1}^{m} \mathrm{e}^{V_k}\right) \tag{5}$$

where A_i denotes the maximum expected utility, and v_{ij} the indirect, or observed transportation, temporal and spatial components of utility. A serious drawback to this approach is that different model specifications cannot be compared. This can be overcome by converting accessibility to monetary, and thus comparable, units by dividing Eq. (4) by a travel-cost coefficient (Ben-Akiva and Lerman, 1985). If v_j is taken as the potential number of activities (jobs, population) within reach, the measure is essentially a monotone increasing function of the potential accessibility measure. The logsum benefit measure has the advantage that it can be linked to micro-economic theory, allowing for calculations of consumer surplus that can be derived by dividing Eq. (4) by a travel-cost coefficient (e.g. Neuburger, 1971; Leonardi, 1978; Williams and Senior, 1978), and to compensation variation, which is derived by dividing the equation by a marginal utility of income, i.e. $\partial v_{ij}/\partial y_i$ where y_i is the individual's income (Small and Rosen, 1981). The logsum measure is not often used in practical applications. Examples are found in Niemeier (1997), who analyses mode-destination accessibility for home-to-work trips in Washington state, and Levine (1998), who analyses the influence of job accessibility on residential housing locations.

A second approach to measuring utility-based accessibility is based on the doubly constrained entropy model. Martínez (1995) and Martínez and Araya (2000) obtained the following accessibility measures from Williams' (1976) integral transport-user benefit measure.

$$A_i = -\frac{1}{\beta}\ln(a_i), \tag{6}$$

$$A_j = -\frac{1}{\beta}\ln(b_j), \tag{7}$$

$$A_{ij} = -\frac{1}{\beta}\ln(a_i b_j) \tag{8}$$

which represent the expected benefits per trip generated (A_i), trip attracted (A_j) and the trip for between zone i and j (A_{ij}), for a given transport situation and subject to trips complying with total trip origins and destinations from the entropy model. These measures should result in similar measurements of economic benefits as the logsum benefit measure, since multinomial logit and spatial interaction models are equivalent formally (Anas, 1983). The advantage of this balancing factor benefit measure compared to the logsum benefit measure is that it allows the additional interpretation of the balancing factors as utility-based accessibility measures including competition effects. However, there are some caveats if the logsum and balancing factor benefit measures are interpreted as measures of consumer surplus or welfare: the measures can only be interpreted unambiguously in monetary terms if the utility function is linear with respect to income, or the policy changes are sufficiently small so that linear corrections of income effects are accurate (see McFadden, 2001).

Current state-of-the practice utility-based accessibility measures satisfy most of the theoretical criteria, except the temporal constraints. There are, however, efforts to reconcile the space–time approach with the utility-based approach. Miller (1999) developed a space–time utility accessibility measure by including the time available for activity participation as a variable in the utility function of the logsum measure. However, this introduces the problems of the person-based measures related to data availability and complexity. In general, the major disadvantages of utility-based measures are the difficult interpretability and communicability. That is the measures cannot be easily explained without reference to relatively complex theories of which most planners and political decision-makers will not have a complete understanding (Koenig, 1980). Clearly, an important advantage is their usability in economic evaluations. That is the measures are able to compute transport-user benefits of both land-use and transport projects, as accessibility changes may be the result of transport changes, land-use changes or both. Thus the measures overcome the shortcomings of using infrastructure-based accessibility measures typically employed in economic evaluations. Utility-based measures also show diminishing returns, i.e. the measures incorporate non-linear relationships between accessibility improvements and user-benefit changes. As a result, the measure may indicate that it is better to improve accessibility for individuals at locations with low accessibility levels (e.g. peripheral regions) than at locations that are already well accessible (e.g. central urban areas) (see e.g. Koenig, 1980; Geurs and Ritsema van Eck, 2001). This is clearly relevant for social and economic evaluations of land-use and transport projects.

4. Conclusions

Accessibility impacts of land-use and transport changes, for example, those due to policies, are often evaluated using accessibility measures, which researchers and policy makers can easily operationalise and interpret, but which generally do not satisfy theoretical criteria. We have described a set of theoretical criteria related to the different components of accessibility from the perspective of evaluating land-use and transport changes. In other words, an accessibility measure should be sensitive to changes in the quality of transport services (transport component), the amount and distribution of the supply of and demand for opportunities (land-use component) and temporal constraints (temporal component). It should also take individual needs, preferences and abilities into account (individual component). These criteria are not considered absolute; applying the full set of criteria would imply a level of complexity and detail that can probably never be achieved in practice. Thus in practical applications, different situations and study purposes demand different approaches. However, it is important to recognise the implications of ignoring one or more of these criteria.

In conclusion, infrastructure-based accessibility measures, such as average speed on the road network, are easy to interpret and communicate but are not very useful for evaluating the accessibility impacts of land-use and transport policy plans since the measures lack the land-use component, and temporal and individual elements. As a result, they may lead to inaccurate or even misleading results if these shortcomings are not recognised and described. More complex 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. That is they 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. Moreover, utility-based measures capture the valuation of accessibility by individuals, providing a useful basis for user-benefit evaluations of both land-use and transport investments. An important remaining theoretical shortcoming is the exclusion of individuals' spatial–temporal constraints typically included in person-based accessibility measures. Person-based measures are potentially very useful for social evaluations, and may also be tied to the utility-based approach, which opens up the possibility of using them in economic evaluations. However, person-based measures still have important disadvantages related to data availability and complexity, restricting applications to relatively small regions and subsets of the population. Furthermore, to date, state-of-the-art, activity-based transport models have not yet been able to link daily activity patterns with long-term spatial behaviour of household and firms, an important shortcoming in evaluations of land-use and transport investments.

Clearly, the current practice of accessibility evaluation of land-use and transport strategies can be much improved by operationalising more advanced accessibility measures that are still relatively easy to interpret for researchers and policy makers, and can be computed with state-of-the practice data and/or land-use and transport models. The most important directions for further research will be explored in the next section.

5. Paths for further research

5.1. Interpretability and communicability

The literature shows a trend towards more complex and disaggregated accessibility measures, partly in response to the recognition that the aggregate measures lack many important details. However, increased complexity increases the effort for calculations and the difficulty of interpretation. For effective evaluations of land-use and transport policy evaluations, there is clearly a need for accessibility measures that are relatively easy to interpret for researchers and policy makers, and which can be operationalised with state-of-the practice data, and land-use and transport models, as well as satisfy the most important theoretical criteria.

The interpretations of more complex location-based accessibility measures can firstly be improved by comparing accessibility across place, time or both place and time, rather than focusing on absolute levels of accessibility. Secondly, the interpretation can be much improved by estimating the separate influence of the different components of accessibility. For example, Geurs and Ritsema van Eck (2001, 2003) computed the separate influence of land-use changes, infrastructure investments and congestion 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. Thirdly, the more complex utility-based accessibility measures can be expressed in monetary values, which strongly improves the interpretability and communicability to planners and policy makers.

5.2. Theoretical improvements

The current practice of evaluating accessibility impacts of land-use and transport policy plans can be much improved by theoretically operationalising more advanced measures that can be computed with state-of-the practice data and/or land-use and transport models.

An initial step towards improved accessibility evaluations is to use more advanced location-based accessibility measures that can be computed with readily available information, and include the transport and land-use components of accessibility. The role of competition effects, for example, in the analysis of accessibility to jobs and health care facilities, needs to be further assessed in practical accessibility evaluations of impacts of land-use and transport policies in different spatial contexts. Recent applications for the Netherlands show that incorporation of job competition affects accessibility. For example, compared to the potential measure, the (inverse) balancing factor shows lower accessibility values, significant up to 20–25%, for central urban and suburban areas, and values in peripheral (rural) areas that are more than twice as high (Geurs and Ritsema van Eck, 2001, 2003). In the case of job accessibility, there is a need for research analysis of job accessibility and competition levels in different situations and spatial contexts (e.g. high-density metropolitan areas vs. low-density rural areas, metropolitan areas in different countries (e.g. Tokyo, London, the Randstad Area in the Netherlands), and for analysis of the influence of land-use and transport policies on job accessibility and competition.

Secondly, there is a need for more research on utility-based accessibility measures in policy evaluations, especially for evaluations of land-use projects and plans, or combined land-use and infrastructure plans, where economic benefits cannot be accurately measured by infrastructure-based accessibility measures. There seems to be surprisingly little experience with utility-based accessibility measures in practical evaluations of land-use and transport policy plans or changes, despite theoretical advantages and their compatibility with state-of-the-practice (multinomial and spatial interaction) transport models.

Thirdly, more research is needed to include an individual's spatial–temporal constraints in accessibility studies allowing more accurate analysis of accessibility. However, work on activity-based models from the last decade was primarily directed towards advancing the methodological state-of-the-art rather than the state-of-the-practice (McNally, 2000). As a result, current methods are still confronted with large problems of operationalisation and data requirements.

Furthermore, as noted earlier, there is still no activity-based land-use/transport model that is able to link daily household activity and travel patterns with long-term land-use changes. Several research paths to develop more practical and operational, person-based accessibility measures do seem possible. Firstly, more simplified activity-based models could be developed which try to generalise observed or simulated activity patterns to system-wide and regional and/or national-scale forecasts, avoiding extensive and expensive data collection typically required for activity-based models. An example of such an approach is the RAMBLAS model (Veldhuisen et al., 2000), which uses micro-simulation of daily activity patterns based on readily available travel data and time use data in the Netherlands. A second approach is described by Thill and Horowitz (1997), who, in the absence of time budget data, treated temporal constraints as unobservable (at least directly) within a random utility framework by assuming a probability distribution of these unobservable time budgets. Thirdly, and finally, if location-based and person-based accessibility approaches cannot be reconciled in one modelling approach, they might be used to supplement each other. This could be done, first, by computing location- or utility-based measures with state-of-the-practice land-use and transport data and/or models for population groups on a more aggregate level, and second, by further specifying these results on more disaggregated and spatially detailed level to unravel person-specific characteristics and particular socio-spatial contexts.

5.3. The use of land-use and transport models and activity-based modelling

The plausibility of an accessibility measure not only depends on how it is operationalised and measured but also on the theoretical basis and practical limitations of the transport and land-use data and models used. Ideally, all feedback mechanisms from accessibility to the different components need to be included. In other words, accessibility is a location factor for inhabitants and firms (relationship with land-use component) and influences travel demand (transport component), people's economic and social opportunities (individual component) and the time needed for activities (temporal component). The inclusion of feedback mechanisms between land-use, travel demand and accessibility implies the use of land-use/transport interaction models. However, not many evaluation studies of the accessibility impacts of land-use and transport projects are based on such models. A state-of-the-practice evaluation would thus involve using a land-use/transport interaction model, which up to now incorporates conventional trip-based travel-demand models (for recent overviews see Wilson, 1998; DSC/ME&P, 1999; Wegener and Fürst, 1999). Besides, activity based modelling might result in a stronger link between the real needs and desires of people to carry out activities at different places, and accessibility indicators for (changes in) the land-use and transport system.

5.4. Option values and non-user benefits

Traditional cost-benefit analyses focus on the transport-user benefit changes for consumers and firms, with travel-time savings as the dominant benefit category (see, for example, the contributions in the special issue of *Transport Policy*, Vol. 7, No. 1, 2000). However, there are two other types of effects related to transport options and accessibility to opportunities that have received little attention, i.e. option values and non-user benefits (see Bateman et al., 2002; Boardman et al., 2001). Option values can be described as the valuation of choice options as a backup for other options or for future use. For example, car-owners may value the ability to use a public transport service when for whatever reason they cannot drive or their car is unavailable. An individual living near the railway line but who do not (intend to) use the rail service with any regularity, may still value having the option to use the service if they choose. Option values are related to the individual's attitude to uncertainty; in practice, a range of option values is likely to be found within the population (DfT, 2000). The second category of benefits, non-user benefits, may relate to the valuation of the very existence of a choice option for individuals or firms (e.g. infrastructure, a nature area), without current or future use, and the valuation of benefits for others (altruistic motives). For example, transport services may be valued by individuals for specific groups such as the handicapped or elderly people. Option and non-user benefit motives may form an important reason for willingness-to-pay through public funds so as to subsidise public transport services (Roson, 2001). Note that both categories can be seen as a social or economic impact (when expressed in monetary terms) as they refer to an individual's valuation of available travel options or opportunities for themselves or for others. So far, very few studies have been conducted on option values and non-user benefits in relation to transport, and there are only a few empirical studies—local public transport services in Italy and the UK (see Roson, 2001; Bristow et al., 1990). Interestingly, the UK Guidance on the Methodology for Multi-Modal Studies (DfT, 2000), the government's appraisal methodology for transport infrastructure investments, includes option values as a sub-indicator of accessibility, although an appropriate appraisal method is lacking. Therefore, appraisal studies use simplified methods to evaluate option values. For example, in the London to Ipswich Multi-Modal Study (LOIS, 2003) the impact of the construction of new railway lines on option values is analysed by estimating the number of residents within an 8 km catchment area of railway stations. However, there is certainly a need for a more thorough theoretical and empirical research to analyse the relevance for social and economic evaluations.

5.5. The incorporation of the different components of accessibility

This review has focused on the question of whether the different components distinguished can be included in the accessibility measures. However, the question of whether the components are included in a theoretically correct manner has not been explored. This is certainly an area for future research. For example, travel time reliability is usually considered very important by travellers, but at present is not included in transport models and accessibility analysis (Bates, 2001). Furthermore, the disutility of travel time might not be constant, as traditionally assumed (Blayac and Causse, 2001; Redmond and Mokhtarian, 2001). And the added value of an increase in the number of opportunities within reach might be subject to diminishing returns, an aspect that is only included in utility-based measures (see Section 3).

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