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Disentangling barrier effects of transport infrastructure: synthesising research for the practice of impact assessment

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Abstract

Transport infrastructure such as railways, motorways and arterial roads increases regional accessibility for motorised transport but simultaneously can create barriers in local street networks that can decrease accessibility for pedestrians and cyclists. Although several tools for an objective assessment of these barrier effects have been developed, their use in practice is limited; impact assessments are instead based on subjective descriptions. This article reviews the literature on barrier effects of the last 60 years and aims to offer guidance for the use of objective methods of assessment of barrier effects. The first contribution is a conceptual model for the barrier effects of transport infrastructure and their determinants. The second contribution is an overview of tools for the assessment of barrier effects. We conclude that a multi-disciplinary approach is required, supported by the conceptual model and the overview of assessment tools. Investments in transport infrastructure can then be based on broader decision support involving not only the benefits of increasing regional accessibility but also the cost of reducing local accessibility.

Keywords: Barrier effects, Severance, Transport infrastructure, Impact assessment, Accessibility

1 Introduction

Transport infrastructure such as motorways, railways and arterial roads can improve accessibility for motorised transport on a regional and inter-urban scale but can at the same time create barriers that reduce accessibility for pedestrians and cyclists on a local scale. These barriers can create detours, reduce opportunities for social contacts, reduce access to workplaces and services, and can make active modes less attractive. Although several indicators and methods have been developed for quantifying the effects of barriers in street networks [3, 40, 104], their application in practice remains limited [8]. Research on barrier effects is also limited compared to other externalities of transport, such as noise and pollution [8].

Instead of objective assessment methods, subjective descriptions are used for the assessment of barrier effects

[8], making it difficult to include in the overall assessment of transport infrastructure projects, and risking inconsistent estimation of barrier effects. This in turn may negatively affect trust between stakeholders, create social and political controversy, and cause delays to infrastructure projects [46]. Further, it creates the risk of poor and incomplete decision support concerning project alternatives, route alignments and design, which can prevent barrier effects from being solved. Incomplete and subjective assessments of barrier effects can lead to a situation where the mitigation measures turn out to be ineffective in practice or even aggravate the barrier problem [67].

Several reasons have been suggested for the limited research attention to barrier effects of transport infrastructure and the limited use of methods for their assessment in practice. The problem is described as very complex [67, 129] as it is difficult to separate barrier effects from other impacts [14]. The dissemination of knowledge of barrier effects is limited because some of the work is hidden in technical reports commissioned by public administrations

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and not indexed in academic databases [8], and is published in other languages than English.

In response, this review aims to disentangle the many factors involved in barrier effects by (1) synthesising the existing research into a simplified conceptual model of barrier effects of transport infrastructure and (2) presenting an overview of the indicators and methods that have been developed for their assessment. Further, we propose that the objective assessment of barrier effects in all its forms require a wide range of methods, techniques and indicators, rather than a single assessment method as is suggested by the reviews of Marsh and Watts [97] and Quigley and Thornley [116] and Tate.

After this introduction follows the presentation of the review methodology in section “[Review methodology](#)”, and section “[A conceptual model of barrier effects of transport infrastructure](#)” offers a conceptual model for disentangling and understanding the barrier effects of transport infrastructure. Section “[What are the determinants of the barrier effects of transport infrastructure?](#)” includes a description of their determinants and in section “[What are the barrier effects of transport infrastructure?](#)” a description of the different levels of barrier effects. Section “[Which tools have been developed for assessing barrier effects of transport infrastructure?](#)” provides an overview of the indicators that have been developed for the assessment of barrier effects. The conclusion presents a reflection on the conceptual model and the assessment tools presented in the article and their implications for practice and theory.

2 Review methodology

2.1 Search and selection process

The literature searches for the review were conducted in March 2019 and complemented with an additional search in September 2020. The databases that were searched were TRID, Scopus and Web of Science. TRID was chosen as it is the largest online database for transport literature. Scopus and Web of Science were added as resources because of their extensiveness.

The following search query was used: (severance OR “barrier effect*”) AND (transport* OR traffic OR highway* OR motorway* OR freeway* OR rail*). No limit was set for the year of publication. The search included all kinds of publications, such as journals and conference proceedings, research reports, governmental guidelines and books. From the search results (n=2 267), duplicate publications and publications not related to transport or to impacts on people were excluded by reading titles and abstracts, reducing the list to 142 publications. Through searches based on the reference lists of these publications, discussions with experts, and broad searches in Google Scholar an additional 169 relevant publications were found, resulting in a total of 311 publications. Of these, 35 publications could not be

retrieved, and nine were written in languages not spoken by the authors. This resulted in a final list of 267 publications, the earliest from 1961 and the most recent from 2021.

The fact that more than half of the relevant literature was not indexed in some of the largest research databases, or could not be found using general search terms, demonstrates the difficulty of getting access to material related to barrier effects. The use of English search terms to some extent limited the coverage of the literature, as this excluded research published in other languages or publications without an English abstract. 75 percent of the publications are academic articles, theses and books, 25 percent are technical reports, guidelines, policy documents and newspaper articles.

2.2 Scope and terminology

In the literature, the term ‘severance’ is frequently used to describe barrier effects of traffic and infrastructure, often in combination with a specification: community severance, physical severance, social severance, secondary severance or psychological severance. There appears not to exist any consensus about the definition of the term, as a review of 60 different definitions shows [4]. Further, the term presupposes the existence of a community before the introduction of a barrier, and it is also used to denote the relocation of residents and businesses for an infrastructure project, but in that case without involving a barrier [61]. The general public has been found to often conflate severance with other nuisances such as noise, pollution and perceived danger [37, 67, 75]. In some studies the term ‘encroachment’ is used [56, 77], which is a broad concept, including land taken for transport, visual intrusion, reduction of the usability of areas near the infrastructure due to emissions and noise, risk of accidents, and negative impacts on wildlife, as well as barrier effects. To avoid confusion, and the risk that the use of specialised terms diverts attention from more important issues [5], the term ‘barrier effects’ is used in this article.

The concept of ‘community cohesion’ occupies a central position within the research on barrier effects, as illustrated by the long tradition of the term ‘community severance’ [8, 28, 37, 76, 116, 141]. Community cohesion is a very broad term also relating to e.g. the values that are shared by people, which creates difficulties in separating barrier effects from other impacts and dimensions of transport in a community. We will use instead the term ‘social connectedness’, which can be defined as a more precise marker of community coherence [116], and is specifically related to the linkages between people, and between people and places of interaction [46] which can be affected by transport infrastructure.

Barriers created by traffic and infrastructure affect opportunities for movement and contact for wildlife in nature [123]. The majority of publications found in the

initial phase of the review are related to these impacts. In this article, however, the focus is on impacts on people. Most studies describe impacts on pedestrian and bicycle traffic, but a study by Rajé [117] shows that residential areas can also be isolated by infrastructural and traffic barriers blocking car traffic. Further, the planning and design of motorways can reduce access to adjacent land use for drivers [17]. Therefore, the review is not limited to impacts on pedestrian and bicycle traffic.

Different terms are used in the literature for different categories of modes of transport, such as ‘motorised/non-motorised’ and ‘sedentary/active travel’. With the introduction of e-scooters, e-bikes and motorised wheelchairs the borders between these categorisations have become blurred. Since differences in speed between different modes can be considered a fundamental rationale underlying the design and planning of transport systems and a central reason why barrier effects arise [67], the categorisation proposed in CROW [40] in ‘fast and slow modes’ is used in the article, unless a specific mode is addressed. The word ‘infrastructure’ is not only used to denote motorways and railways but also all other constructions built for transport purposes, including roads and tramways.

Publications that refer to barrier effects as an impact of transport or simply include barrier effects in a collection of negative impacts of transport on health, social contacts, use of the street and the environment, without specifying the role of barrier effects, were not included in this article.

3 A conceptual model of barrier effects of transport infrastructure

Barrier effects are concomitant effects of transportation systems comparable to noise, pollution and vibration. However, an important difference is that the latter three are emitted from the traffic on the system regardless of its context. In contrast, barrier effects are described as an emerged phenomenon [91] that is determined by several factors; a transport feature becomes a barrier only when it is in the way of someone on their way to somewhere. As a consequence of this multi-factor character, barrier effects cannot be assessed as an isolated externality, but require the engagement of several stakeholders and competences. This creates a need to distinguish firstly, the barrier effects from their determinants, secondly, the relations between different determinants, and thirdly, the different levels of barrier effects. To disentangle these aspects, Fig. 1 presents a conceptual model for the barrier effects of transport infrastructure, describing the determinants and levels of these effects.

Concerning the determinants of barrier effects, following Korner [87], CROW [40], Boon et al. [26] and Ancaes et al. [8], five determinants can be distinguished: (1) transport features, (2) crossing facilities and routes, (3) people’s abilities, (4) land use, (5) people’s needs. In order to express how the interplay between the determinants results in changes in barrier effects, relations between determinants are here described using mathematical operators. The intention with this notation is to express these relations in a concise way that broadens the perspective on barrier effects from a focus on the transport feature to inclusion of the other four determinants in an equal way. It might be possible to develop the

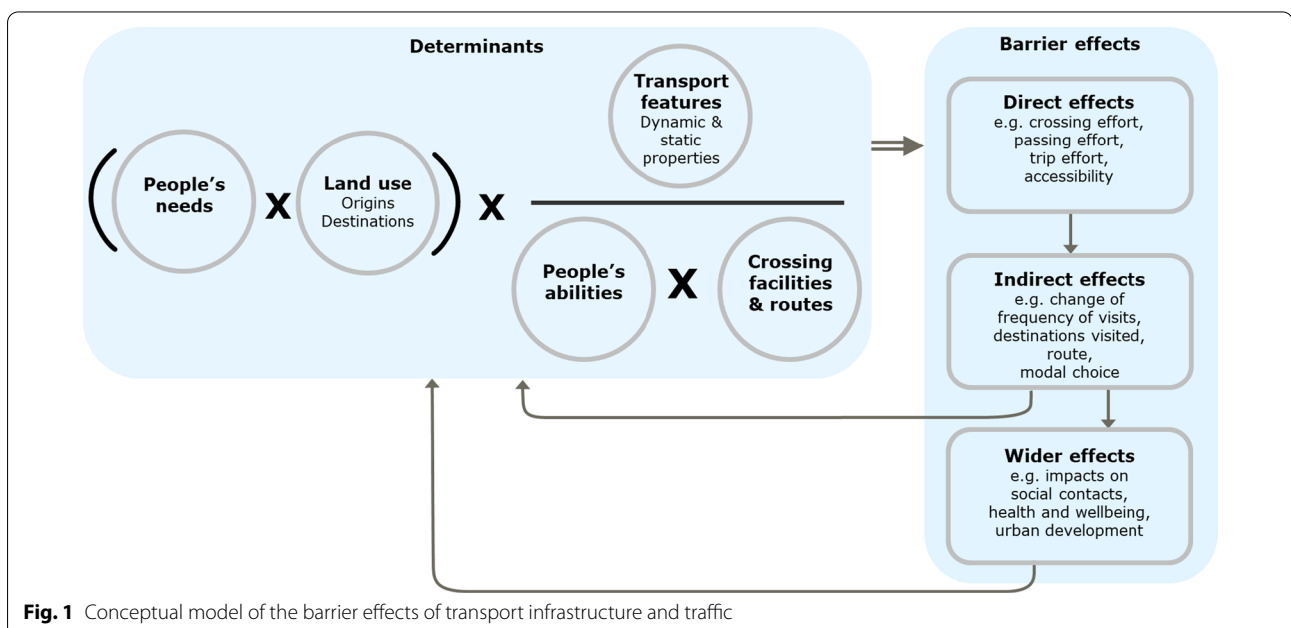


Fig. 1 Conceptual model of the barrier effects of transport infrastructure and traffic

model further into a mathematical equation, this however requires further investigation and lies outside of the scope of this review.

Some examples can demonstrate the rationale behind the relations between the determinants. Due to the intensity of traffic and the presence of physical barriers, such as fences and noise screens, a transport feature like a road can limit opportunities to cross. Therefore, in the model, an increase in the separation value of ‘Transport features’ leads to an increase in barrier effects. If a transport feature has no separating characteristics, for example, a footpath in a residential neighbourhood, its separation value is zero and there are no barrier effects, regardless of the values of other determinants. The impact of the separating characteristics of a transport feature can be reduced by the value of the determinant ‘Crossing facilities and routes’ (such as bridges, tunnels or pedestrian crossings), that create opportunities to cross. These opportunities are further determined through the position of the crossing facilities in the street network and their quality. However, if an individual’s ability to cross is limited, due to age or ability, the value of ‘People’s abilities’ is lower and barrier effects increase. For individuals who are unable to cross, the barrier effects of a transport feature become very high, no matter how few separating properties it might have. The determinant ‘People’s needs’ defines the needs of people to reach certain destinations, whereas the determinant ‘Land use’ defines the need to cross due to the presence and location of destinations. These two determinants combined define the demand to cross the transport feature. For example, if children live on the same side of the railway as their school, they experience no barrier effects of the railway. If the school is relocated on the other side of the railway (a change to the determinant ‘Land use’), barrier effects arise. If the number of children in the area decreases (a change to the determinant ‘People’s needs’), barrier effects are reduced again.

Regarding the levels of barrier effects, most authors make a distinction between direct and indirect effects. Like Mouette and Waisman [108] and Korner [87], we have chosen to further split the indirect effects into indirect and wider effects, as this allows the distinction of different areas of responsibility and competence involved in the assessment process. We therefore categorise barrier effects according to a three-level hierarchy (Fig. 1) where transport behaviour is the distinctive element: (1) direct effects: extra travel efforts that occur when a new transport feature is constructed or when the deterring characteristics of an existing transport feature changes, such as an increase in traffic; (2) Indirect effects: changes in travel behaviour when the extra efforts caused by the barrier pass the acceptance level of the individual; (3) Wider effects: impacts of the changes in travel behaviour on

individuals and society at large. The model (Fig. 1) represents the role played by time, both on barrier effects and their relations with the determinants. Barrier effects can create positive and negative feedback loops in the system by impacting the determinants from which they originate [87]. An example of such a feedback loop occurs when a busy road motivates people to drive instead of walk or cycle (indirect effect). This leads to an increase in car traffic on the road (transport features determinant), affecting the crossability or passing effort (direct effect), and can lead to more people choosing to take the car and further increase of barrier effects [67].

4 What are the determinants of the barrier effects of transport infrastructure?

4.1 Transport features

Transport features are the central determinant in the process of how barrier effects arise. The attention on barrier effects has grown together with the growth in car traffic in cities, and the literature is mainly focused on the determinant role of this mode of transport. However, infrastructural barriers can be defined as all forms of transport infrastructure that reduce or remove opportunities for movement from one location to another, including railways and waterways. Based on Ancaes et al. [8], Héran [65, 67] and Korner [87], Table 1 presents the physical and psychological properties of transport features that determine their barrier effects. Also listed are separating aspects of transport features that depend on formal regulation rather than physical boundaries.

Table 1 follows the distinction between physical and psychological barriers often made in the literature. Sometimes these categories are described as “real” and “perceived” barriers [32, 58], terms that could be interpreted as a value statement. We define physical barriers as *objective* barriers, related to characteristics that exist without a person being present, and psychological barriers as *subjective* barriers, related to psychological reactions to the built environment that can vary from person to person and do not occur when no one is present. Psychological aspects of transport features are concerned with *conditions* that can lead to various psychological reactions (barrier effects of different levels, see section “What are the barrier effects of transport infrastructure?”). For example, the nuisances of traffic, such as risks of accidents, noise, pollution, dust and vibrations, can create a separating effect without physically hindering travel behaviour.

4.2 Crossing facilities and routes

The planning and quality of crossing facilities [95, 99] and of crossing routes [40, 67] further determine

Table 1 Properties of transport features that determine barrier effects

Properties	Type	Description
<i>Physical</i>		
Static	Motorways and feeder roads, railways, waterways	Fences, railings, noise screens, height differences (embankment, ditches), road width, traffic isles, visual conditions at crossing points [22]
Dynamic	Transversal, across a feature (car or tram traffic)	Traffic flow, traffic direction, speed, proportion of heavy vehicles, parked vehicles [8], bunching of vehicles [57], waiting time at controlled crossings [87], snow clearing
	Longitudinal, along a feature (car or tram traffic)	Traffic flow, speed, proportion of heavy vehicles, parked vehicles [67], affecting mostly bicycles [48, 67, 87]
<i>Psychological</i>		
Characteristics of transport features and their environment that have a deterring effect without creating a physical barrier	Conditions for fear of accidents	Experienced risk of traffic accidents occurring when crossing or travelling along a transport feature [70, 78]
	Conditions for fear of crime	Lighting, visibility, escape opportunities, social surveillance [6, 142]
	Conditions for discomfort	Noise, pollution [60, 92], dust [30], smell, vibrations, splashes, less attractive routes [40], amount of scrap on and around crossing facilities [88]
<i>Formal</i>		
Traffic rules		Traffic lights, possibility for manually controlled traffic lights, one-way streets [87], parental rule that a child is not allowed to cross a road [87, 130]
Planned infrastructure projects		Reserves in land use planning documents can create zones that form a barrier for transport [31, 43], uncertainty about the possible barrier effects of planned infrastructure can impact land prices and urban development [127]

opportunities to overcome barriers. Table 2 lists properties that have been identified as determining barrier effects.

The importance of the frequency and location of crossing facilities varies for different modes. For car traffic, travel time is the most defining factor. For slow modes, since they often involve muscle power, distance is a more

sensitive parameter, as the numerous shortcuts and ‘elephant paths’ (informal footpaths trampled over time) in our cities demonstrate [40, 67]. These two principles, travel time and travel distance, combined with the need to create safe traffic environments, have led in many cities to the development of two separate traffic networks: one tree-like, hierarchical network for fast modes that allows

Table 2 Properties of crossing facilities and routes that determine barrier effects

Properties	Description
<i>Crossing facilities</i>	
Number of crossing points	Slow mobility modes require a higher number of crossing points than fast mobility modes [40, 67]
Height differences	Stairs and ramps leading to bridges and tunnels [6, 67]
Integration in the local street network	Connection to routes or central mobility strips [131]
Visual conditions	Lines of sight and overview at crossing points on roads [22, 87]
Conditions for fear of crime	Lighting, visibility, escape opportunities, social surveillance [6, 142]. For a further description, see section “Transport features”
Quality	Protection from weather, maintenance [6], design and cleanliness [88]
Formal regulation	Pedestrian crossings, traffic lights and possibility to manually control these [87]
<i>Crossing routes</i>	
Number of crossing routes	Utilitarian and recreational routes for slow mobility that cross the transport feature [40]
Connectivity of the street network	Mesh width [40]
Density of the street network	Network length per hectare or km ² [67]
Attractivity	Planning, design, signage, cultural-historic value, level of traffic safety [6, 40]

for differentiation of speeds in connecting and distributing traffic, and one network for slow modes that is finely gridded and allows for shortcuts [67]. The superposition of these two networks in cities leads to many overlaps (longitudinal) and crossing (transversal) conflicts, the latter solved with different crossing facilities that often require extra effort, detours, or waiting for slow modes.

4.3 People’s abilities

The actual impacts of the separating characteristics of a transport feature and the availability of crossing facilities and adequate routes are determined by people’s abilities, related to both crossing and moving along the actual transport feature, as well as travelling across a larger area that is created for a transport feature and its safety zones. Table 3 lists some of the factors that define people’s abilities to overcome barriers.

Age is identified in the literature as the dominant factor for dealing with barriers; besides being listed as a separate factor in Table 3, age is also linked to the other factors listed. Gender is another aspect often mentioned in the literature; related factors are: physical capabilities, limited or no access to a car due to the role in the household, responsibility for accompanying others, and pregnancy. A further example of how gender forms a factor is the way many parents in African cities are reluctant to let

their daughters walk along major roads and unsafe paths [30].

Modes of transport determine the possibilities to move across the built environment as they give or restrict access to transport networks and spaces. The studied literature strongly focuses on barrier effects on cyclists and pedestrians, while Rajé [117] demonstrates that car traffic from residential neighbourhoods can also suffer from the barrier effects of busy roads.

4.4 Land use

Land use plays a passive role in the location and extent of barrier effects through the spatial distribution [93] and density of both residential addresses and facilities. But land use can also play an active role when the spatial distribution and density of land use changes, which can increase, decrease or relocate potential needs to cross [3, 17, 67], for example, the expansion of residential areas and the relocation of sports clubs or schools to the ‘other side’ of motorways and railways [40, 67]. Functional separation in cities also contributes to barrier effects by separating residential zones from retail, service and industry zones, which increases travel distances and creates the need to cross the transport infrastructure located between these zones [87] (Table 4).

Table 3 Factors that define people’s ability to overcome barriers

Factor	Description
Age	Sensorial, cognitive and practical constraints of children and older people [35, 70, 103, 136]
Mobility restrictions	Physical and psychological capabilities [67] Pregnancy [67] Accompanying others (e.g. pram or wheelchair) [67, 108]
Mode of transport	Carrying luggage/shopping [67]
Limited or no access to a car	Foot, bicycle, public transport, car [8, 117] Role in the household [67] Environmental concern [18, 67] Financial restrictions [130]
Knowledge restrictions	Awareness of transport options [130]

Table 4 Aspects of land use that contribute to barrier effects

Aspect	Description
Distribution	Location of residential addresses and facilities within the area affected by a barrier [35, 67]
Density	Density of residential addresses and facilities within the area affected by a barrier [3, 42]
Quality	Differences in the quality of service or products offered on both sides of a barrier [26]
Temporal availability	Opening hours of facilities [26, 130]
Substitutability	Available choice of alternative facilities [17, 130]

Table 5 Factors that influence people's needs to visit destinations involving trips across or along a barrier

Factors	Description
Age	Averages of daily trips, e.g. to playgrounds, bus stops, services for different age groups, can be derived from travel surveys [48]
Socio-economic	Income, employment, role in the household, lifestyle orientation and preferences [83] leading to restrictions in choice of residential location, workplace, education, shopping [8, 67]
Social connectedness	The more a person is dependent on local social contacts, the stronger the need to cross a barrier if these local contacts are within the neighbourhood located on the other side [130]. In contrast, more mobile social groups are described as less sensitive to barrier effects [130]

4.5 People's needs

While the four determinants described so far all contribute to the *potential* barrier effects of a transport feature, it is through the needs of people that barrier effects are actualised [126] (Table 5). *Actual* barrier effects arise only when a person needs to visit a facility on the other side of a road that is too busy for crossing, or when a person is not able to take the stairs of a bridge over that road, or where no crossing facility is provided. The needs to visit social contacts, facilities, services and amenities vary for different groups and individuals. Boon et al. [26] distinguish three general groups of needs: self-fulfilment, social interaction and consumption. Different sets of destinations to fulfil the needs of people have been proposed, such as health, education, services, social, leisure, shops and transport [37, 46].

In impact assessments, the focus generally lies on people who are resident in the study area, but as many trips have other starting points than home, the perspective of workers and visitors in the area also needs to be considered [8, 130]. Barrier effects can also impact business and services in a different way than residents. Losing access to a supermarket will have less of a cost for a resident if a new supermarket is established within reach, however, for a supermarket the loss of customers can have significant consequences [46, 133].

As impacts cannot be assessed for each resident separately, some form of categorisation of groups must be made. Many general categorisations of people have been suggested for the assessment of effects of changes in transport systems [69, 81–83], and with a specific focus on groups that are vulnerable to barrier effects (see section “People's abilities”) [37, 46, 67, 91, 119]. However, it is likely that different categorisations need to be established for the specific cultural context, type and scale of the project or situation that is being assessed.

5 What are the barrier effects of transport infrastructure?

5.1 Direct barrier effects

Direct barrier effects (Table 6) are the inconveniences that people experience and sacrifices they must make due to separating ‘Transport Features’. The defining

characteristic of direct barrier effects is that they occur when people keep their ordinary travel behaviour and accept the inconveniences and sacrifices, either because the level of the barrier effects does not exceed their acceptance level or because there is no alternative. Table 6 lists the direct barrier effects of traffic and transport infrastructure.

Extra effort to cross or pass along a transport feature is the primal direct effect of barriers. Fear of crime, like fear of traffic accidents, is an emotional reaction to the perceived physical and social environment [140] that can create psychological barriers (see section “Transport features”). It is therefore a type of crossing effort. Because of its complexity, it is presented here as an individual effect. Defined by a wide range of factors, on an individual, group as well as environmental level [142], it is typically related to the enclosed spaces of underpasses [6]. It involves both the direct fear of becoming a victim, which can affect travel behaviour during a trip, and anxiety about the risk of becoming a victim, which can lead to long-term changes in travel behaviour.

5.2 Indirect barrier effects

Indirect barrier effects comprise the various changes in travel behaviour that occur when direct barrier effects exceed the acceptance level of a person. These behaviour changes can relate to travel frequency, destination, route, time, or transport mode (Table 7). Acceptance levels of individuals are not fixed and can change; consequently, indirect effects can alter over time [91].

The indirect effect of mode of transport can cause a negative feedback loop where a modal shift from walking and cycling to car travel can increase car traffic on roads and increase direct barrier effects [40, 67].

5.3 Wider barrier effects

Wider barrier effects involve the impacts on individuals, groups and society at large of changed travel behaviour due a barrier. These effects involve many dimensions and aspects and are therefore hard to reduce to a concise list. Instead, we will describe some of the general groups of wider barrier effects found in the literature.

Table 6 Direct barrier effects of traffic and transport infrastructure

Effects on	Description
Crossing effort	Delays, physical effort, discomfort, stress, and fear of traffic accidents while crossing a transport feature, due to its static or dynamic barrier characteristics or the quality, design or planning of crossing routes and facilities (transversal barriers, see section “Transport features”) [6]*,[18], [29], [71]*,[76]*
Passing effort	Physical effort, comfort, stress and traffic risks while passing along a traffic feature, affecting cyclists especially (longitudinal barriers, see section “Transport features”). [67, 87, 104]
Fear of crime	Fear and anxiety about becoming the victim of crime, typically related to crossing facilities [6]*
Trip effort	Extra travel time, physical effort, comfort, stress and cost for trips, e.g. to schools, workplace, facilities and social contacts. [29]*,[31]*,[39], [59]*,[76]*,[107]*,[108]* Detours and delays at level crossings that lead to increased travel time and reduce the reliability of service vehicles such as mail and waste collection [38, 67, 95, 111] and public transport [41] Change in the number of routes available to reach a destination [40, 97] Change of possibilities for drivers to access destinations located adjacent to a road [17], when the road is upgraded to motorway standard, possibilities to park at the roadside are removed and the number of exits are reduced Travel time between different parts of a farm [20]
Accessibility	Change in the available choice of opportunities within a given travel time or distance [31]*,[40], [50], [108]* Change of consumer base of facilities, measured as the change in the number of residents within a certain travel distance of time from a facility [17, 37, 91, 130]

* Empirically supported effect

Table 7 Indirect barrier effects of traffic and transport infrastructure

Effects on	Description
Frequency of visits	When trips take more effort due to a barrier, the frequency of visits can change or motivate people to suppress trips all together [9]*,[71]*,[96]*,[108]*
Visited destinations	Changes in accessibility can motivate people to reorient themselves regarding shops they usually visit, looking for opportunities that do not involve crossing [50, 62, 108]*
Routing of trips	Routing of trips can be changed to avoid barriers [40]
Organisation of trips	Timing and organisation of trips can be changed, with people combining different destinations in one trip [59]*, [71]*
Mode of transport	Increased distances or changed levels of traffic safety can make people change mode, typically choosing to drive instead of walk or cycle to everyday destinations [47]*,[76]*,[115]*

* Empirically supported effect

The most prominent wider barrier effect mentioned in nearly all studies and reports is the impact on social contacts and social connectedness. Important studies were carried out in the late 60 s, 70 s and 80 s by Appleyard and Lintell [12, 13], who demonstrated that people living in streets with high levels of traffic had fewer social contacts with their neighbours than people living in streets with less traffic. Also, people living on busy streets indicated that their neighbourhood was smaller than that of residents on lightly trafficked streets. The findings by Appleyard and Lintell had been previously demonstrated by Bryan [34] and have since been confirmed in several studies [27, 63, 86, 98, 125, 135, 143]. A limitation of these studies is that they analyse the combined impact of noise, pollution and traffic risks on social contacts which makes it difficult to isolate the specific impact of traffic as a barrier.

Lee and Tagg [93] studied the impacts of barriers on social contacts specifically, demonstrating that, despite what was expected and contrary to the results of Appleyard and Lintell [12, 13], the areas indicated by residents as their neighbourhood were larger in locations near a motorway than comparable locations without a motorway. Neighbourhoods near older motorways were even larger but were found to grow away from the barrier. Fewer trips across the motorway were recorded and residents also had fewer social contacts across the motorway. However, this last effect was found to diminish over time. Further, barriers can force people to choose cars rather than walking or cycling (an indirect effect, see section “People’s abilities”), which reduces possibilities for social contacts and social connectedness [29, 76]. The discontinuities caused by barriers reduce the free flow of people on the street network, and can decrease diversity and mingling of people on the streets [73].

The second group of wider barrier effects that is often mentioned are impacts on health and wellbeing, even if a direct causal relationship is hard to establish [44, 102]. Negative impacts on health occur due to reduced opportunities for social contacts [25, 103, 126], for active travel [25, 80, 90, 102], and reduced accessibility to health services, to shops with healthier food products and to facilities for physical activity [25, 39, 102, 103]. Barriers can lead to feelings of being cut off, including missing the passive utility of knowing that the opportunity of access to facilities exists, for example, availability of a hospital, giving a feeling of security [130]. Busy streets can reduce possibilities for children's independent play which has been connected to reduced motor and social skills and independence of children [128], although it is unclear if the reduction in children's play is related to difficulties in crossing streets rather than to noise, pollution and traffic safety. For older people, barriers can lead to restricted freedom of movement, affecting their experience of independence and engagement in social networks, which affects physical and mental health [59, 80, 101, 126].

Barriers also have wider effects on urban development and economic activity that extend over larger temporal and geographical scales. An example are railways and stations, often playing a key role in the historic development process of cities, both attracting and generating movement as well as forming a hindrance to movement [19, 113]. Such infrastructures can disrupt the street network in the vicinity to the station, and lead to a process of degradation and concentration of poverty [23, 24]. This segregating effect of motorways and railways has also been used intentionally for the enforcement of socio-political agendas, as cases in South Africa [30] and in the US [100] demonstrate. Although no causal relations were established, different studies showed cases where barriers like motorways and major roads coincide with boundaries between ethnic groups in the US [110], between vulnerable social groups [85], and between income levels of neighbourhoods [105]. Additionally, the effect of large roads as barrier against crime has been studied, with apparent contradictory results. While some studies show no reduction in crime [114, 118], other studies show how roads and other types of barriers do contribute to reducing crime [16, 36, 144].

On a more local scale, reduced numbers of passers-by in the vicinity of transport infrastructure barriers can increase the fear of crime, and create a negative feedback loop in which more people avoid the area around infrastructure, turning it more desolate. Similarly, barriers can cause a decrease in economic activity [51, 72, 119] and a reduction in the customer base of commercial and public facilities, leading to negative impacts on their capacity and quality [46, 87, 133]. If traffic in a multi-functional

street is prioritised over its function as a service centre for the surrounding area, its role as magnet for economic and social activity can disappear, leading to a decline in the number of businesses located there [38, 73, 95]. Outside of urban areas, barriers can fragment recreational areas and recreational road networks [64, 132].

6 Which tools have been developed for assessing barrier effects of transport infrastructure?

Several tools have been developed for the assessment of barrier effects of transport infrastructure, to be used individually and as part of an assessment method. The following overview is organised on the same three levels as barrier effects. Besides indicators and assessment methods, monetisation techniques have been proposed for the assessment of barrier effects. As these are not connected to a specific effect level, they are presented in a separate subsection.

6.1 Indicators of direct barrier effects

The majority of indicators that have been developed deal with direct effects. Table 8 lists the indicators of direct barrier effects found in the literature, categorised according to the effects they relate to.

A central aspect of the trip effort and accessibility indicators is the selection of destinations considered, and different sets of destinations have been proposed [37, 46]. Which destinations are of importance depends on the social and geographic context of the study area, the character and scale of the project, and the issues that are being assessed. It is important to consider that the indicators involving land use give no insight into the actual demands of people [126], that the accessibility needs of people vary, attitudes and reactions from residents can change over time [8], and that changes in transport systems can create conditions for the establishment of new services that replace old ones of lesser quality [46].

A different perspective can also be applied to the assessment, shifting focus from measuring barrier effects of a transport feature to measuring the potential improvements of alternative solutions of new crossing facilities to reduce barrier effects. An example of this can be found in Andersson et al. [11] who assessed locations for a bridge across a river by looking at increase in accessibility to workplaces and travel time savings offered by different alternatives.

6.2 Indicators of indirect barrier effects

Table 9 presents the indicators for indirect barrier effects found in the literature. Given that these effects relate to changes in travel behaviour, most indicators are based on surveys and interviews. Russell and Hine [122] emphasise that travel behaviour is based on subjective perception of

Table 8 Indicators of direct barrier effects

Effect on	Indicator	Description	Technique			
			Video observation and traffic counting	Site audits	Surveys and interviews	Geospatial analysis
Crossing effort (static characteristics)	Localisation of transport infrastructure	[21, 40, 87]				X
	Road width	Road width that needs to be crossed in meters [21, 40, 87]		X		X
	Number of lanes	[21, 40, 87]		X		X
	Hindrances along infrastructure	Fences, noise screens, etc. [21, 40, 87]		X		X
	Width of central reservation	[21, 40, 87]		X		X
	Visual conditions at crossing facility	Lines of sight at the crossing facility [21, 40, 87]		X		X
	Height differences	Bank on which the transport feature is located or if the feature is placed in a trench [21, 40, 87]		X		X
Crossing effort (dynamic characteristics)	Speed	km per hour [40, 99, 122]	X			
	Volume	Vehicles per hour [40, 99, 122]	X			
	Vehicle composition	Proportion of heavy vehicles (trucks, busses) in the total traffic flow [40, 99, 122]	X			
	Direction of traffic	Left/right [40, 99, 122]		X		X
	Distribution of acceptance gaps	Related to the grouping of passing vehicles, measured by adding reaction time, crossing time and a safety margin. It must be considered that different social groups (e.g. age groups) have different reaction times, crossing times and safety margins. [57, 58, 122]	X		X	
	Parked vehicles	Number of parked cars along a street [67, 122]		X		
	Risk of traffic accidents while crossing	Number of traffic accidents on a given stretch or point [99]	X			
Crossing effort (facilities)	Distance to a crossing facility	Distance between a street connection with the barrier and the nearest crossing facility [99]			X	
	Delay at crossing facility	Waiting time for the next opening of a railway or road crossing facility or next ferry crossing. Possibility to control traffic lights manually [40]	X		X	X
	Effort required for use of crossing facilities	Height difference to be overcome at bridges over and tunnels under the transport feature [67]		X		
	Protection from weather conditions at the crossing facility	Roofs and screens at bridges for shelter from rain and wind [6, 67, 95]		X		
Passing effort	Volume	Vehicles per hour [48, 67, 130]	X			
	Vehicles composition	Proportion of heavy vehicles (trucks, busses) in the total traffic flow [48, 67, 130]	X			
	Frequency of overtaking	Number of vehicles that overtake a cyclist [48, 67, 130]	X			
	Speed	km per hour [48, 67, 130]	X			
Fear of crime	Social surveillance	Presence of "social eyes" from entrances, windows, passers-by and surveillance cameras [142]		X		
	Escape options	Number of alternatives for exiting the crossing facility [142]		X		
	Visual conditions	Level of lighting in and around the crossing facility and area around the transport feature. Possibilities for an overview [142]		X		
Trip effort	Distance between crossing facilities	Distance between crossing points; benchmarks: within urban environment max 300-500 m, outside urban environments max 1,000–1,500 m [6, 9, 40, 67]				X
	Distribution of crossing facilities	Number of crossing facilities per km along the barrier [40]				X
	Number of barriers along routes	Number of barriers along existing slow mobility routes (utilitarian and recreational) weighted by e.g. attractiveness, presence of signage and its cultural heritage value [40, 64, 67, 132]				X
	Number of disconnected streets	Number of streets that are not connected due to the presence of a railway station and railway [120]				X

Table 8 (continued)

Effect on	Indicator	Description	Technique			
			Video observation and traffic counting	Site audits	Surveys and interviews	Geospatial analysis
	Detour factor	Ratio of network distance and straight-line distance between given origins and destinations [40, 66, 67]. Benchmarks for average detour ratio: 1,15–1,25 in urban areas, 1,3 in regular grids [67]				X
	Closeness	Proximity of single street segment to all other street segments within a given travel distance [23, 42]				X
	Betweenness	Frequency of street segments being part of paths with least impedance between one street segment and all other street segments [42]				X
	Isodistance	Ratio of area reachable with a given street network distance and area within the same distance measured as straight line [67]				X
	Proximity to destinations	Network distance/travel time/travel cost from each address point to the nearest facility within a given group of facilities. Also, the number of households affected by longer travel distances to a given selection of facilities can be calculated [14, 15, 138]				X
Accessibility	Travel time for service vehicles	Travel time for service vehicles such as ambulances, public transport and waste collection [41, 67, 95, 138]				X
	Catchment areas for facilities	Number of residents or households within the catchment area of each facility within a given category of facilities. Catchment areas are measured using network distances and are defined as overlapping or exclusive areas [37, 138]				X
	Choice/substitutability of destinations	Number of destinations within a given group of destination that are accessible from each address point within a given travel time. The effect of the barrier will be lower if more than one destination is accessible [50, 130, 133, 138]				X
	Accessibility to employment	Accessibility to job opportunities, measured by number of jobs or revenue of the workplace, inversely weighted by travel time [2, 76]				X
	Degree of separation	“Physical severance index” [35]. Distribution of built area (in sq.m.) and distribution of destinations on both sides of a barrier, expressed as index values. The barrier effect is highest when the built areas and destinations are equally divided on both sides, as this implies the highest level of communications that can be affected. When the built-up area and activities are on one side only, the barrier effect is lowest [35]				X
	Lost population-interaction potential	Number of potential meetings between residents from different neighbourhoods at a common facility that are affected by a barrier [3]				X
	Land use connectivity	Number of barriers that are crossed by straight lines drawn between neighbourhoods and neighbourhoods or between neighbourhoods and given destinations [2, 40, 46]				X
	Access from roads	Number of exits from a road and travel time for drivers to reach destinations directly adjacent to the road [17]				X

the physical environment, and argue, like many others [8, 26, 109, 127], for the importance of combining qualitative methods such as surveys and interviews with quantitative methods. Interviews especially are described as an important tool as some responses to barriers, such as avoiding road crossings, are impossible to observe [68].

The measurement of suppressed trips offers a challenge, as these trips do not involve behaviour that can be observed directly [68]. The demands that exist within a population can sometimes be revealed only when new services are established [126]. Tirachini [134] used general statistics of travel behaviour to estimate the probability of trips-not-made. If in a specific geographical

Table 9 Indicators of indirect barrier effects

Effect on	Indicator	Description
Frequency of visits	Ratio of changes in number of visits	Percentage of interviewees who indicate they changed the number of visits they make to destinations and social contacts or decided not to make some of these trips to avoid a barrier [9, 10, 71, 108]
	Suppressed pedestrian trips	Number of trips missing in travel behaviour statistics, relative to averages for comparable places. Missing trips can be assumed to be suppressed or that a different mode was chosen [134]
Visited destinations	Ratio of changes in destination of trips	Percentage of interviewees indicating that they changed the range of destinations they visit [108]
Routing of trips	Crossing ratio	"[N]umber of pedestrians who cross a road as a proportion of the pedestrian flow, over a given section or at a specific point" [122]. Registration through video observation
	Ratio of changed routes	Percentage of interviewees indicating that they changed their route planning [59, 71]
Organisation of trips	Ratio of changes in timing and organisation of trips	Percentage of interviewees indicating that they changed their trip timing and organisation [68]
Mode of transport	Modal share	Number of trips that, due to barriers, are made with another than the preferred mode, typically foot and bicycle [29, 47, 71]

area a certain range of short trips is missing compared to general travel behaviour statistics, it may be assumed that these trips are either suppressed or that a different mode was chosen. The study also estimates the probability of people travelling certain distances, defining a threshold after which the probability that people travel by bicycle or on foot drops. The crossing ratio suggested by Russell and Hine [122] allows for the measurement of effects of changes in dynamic and static characteristics of a road, for example when due to a change in the road network the traffic intensity increases. If fewer people cross a street than in comparable situations, there is a possibility that trips are being rerouted or suppressed. The large variations that exist between the character of different streets presents another challenge for this indicator.

Traffic counting at crossing facilities is a conventional approach for estimating indirect barrier effects and making prognoses regarding changes in crossing behaviour due to changes in transport features. But this approach only considers the characteristics of a transport feature and crossing facilities, and disregards the role that routes, people's abilities, land use and people's needs have in the level of barrier effects, and where they can arise. This can lead to misestimations of barrier effects and incorrect decision support regarding planning and design on new crossing facilities [31]. Another misconception is to compare the number of people using a certain crossing facility with the number of people using the transport feature [67]. As described in section "Crossing facilities and routes", slow mobility networks commonly have a spread-out distribution compared with the concentrated flow of fast mobility networks. For a fair comparison, the flows at crossing facilities should be recorded over a longer stretch of the transport feature and compared with the flow on the transport feature itself [67].

6.3 Assessment of wider effects

As described in 5.3, wider effects are generally complex, involve many factors and are often characterised by a development over time. In contrast to direct and indirect effects, few explicit indicators or methods for measuring wider effects have been described in the literature. Their assessment is instead part of broader social impact assessments of transport systems that also include the consequences of other impacts of transport, such as noise and pollution. A central challenge for the assessment of wider barrier effects is that little has been done to translate the concepts from social theory to which they relate, to practical tools for assessment [50, 52]. An example of this is the concept of 'social community', central to much of the research on barrier effects, yet one that is difficult to define objectively. This can be seen as an instance of the hindrances for including barrier effects in the objective assessment of transport infrastructure projects. Furthermore, it is difficult to aggregate the conclusions from the assessment of different types of wider barrier effects into cohesive decision support, given that these assessments often involve different types of valuation, or different scales and units.

Some approaches and methods for assessing the impacts on social contacts were found in the reviewed literature. Hine and Russell [71] and Ogilvie et al. [112] describe their approaches to performing interviews with residents regarding the social impacts of barriers for example. Similar surveys and interviews, comparing neighbourhoods with and without a motorway as a barrier were undertaken by Lee and Tagg [93]. Risks in these assessment methods are reverse causation (such as, low wellbeing causing people to experience traffic as a barrier instead of the other way round) and residual confounding (such as, poor people with low wellbeing can only afford cheaper apartments that may be located near busy roads) [9].

Changes over time in the land use and street networks around station areas have been studied using different techniques for longitudinal morphological analyses [23, 24, 113]. A method for studying correlations between residential locations of different socio-economic groups and barriers in cities is presented by King [84]. Similar studies concerning the correlation between socio-demographic characteristics of residents and the quality of the nearest railway crossing (measured as traffic volume, lighting conditions, width walkway, height differences etc.) were presented by Lara and Rodrigues da Silva [88], who repeated their study in a case of crossings over an urban motorway [89].

6.4 Monetisation

A generally accepted way of dealing with the challenges of aggregating the results of different impact assessments into decision support is monetisation, that is, representing all impacts with a unified monetary value. Table 10 lists a range of techniques for the monetisation of barrier effects that have been developed.

These monetisation methods are well established within transport investment appraisals and offer the benefit of making it possible to compare externalities of transport systems that are otherwise impossible to compare. The monetisation techniques, except for those based on estimated values and objective valuations, allow for the judgements of the general public to be included in the decision process instead of being based on expert judgements only.

Some challenges in the application of these methods can be mentioned. Estimated monetary values suffer from the problem of subjectivity [121], which goes against the very motivation for attempts at quantification and monetisation. Hedonic modelling typically does not offer understanding of the motivations behind WTP for housing or real estate. Further, it is difficult to isolate barrier effects from other factors that correlate with it, such as noise. An example is the hedonic study by Kang and Cervero [79], often cited as an example of monetisation of barrier effects. It is not clear if the increases in real estate prices presented in the study are due to the introduction of a park, or the removal of noise and other externalities, or if they are due to the removal of a motorway as a barrier. Depending on the design of the choice modelling or contingent valuation surveys, participants can find it difficult to understand the alternatives offered with regards to distance, time, speed and non-visual stimuli [119]. A more general critique of monetisation techniques is that they can lead to a focus on cost-efficiency of the project, and not on general equity for society, and that there is often a disregard of the link between ability to pay and willingness to pay [137]. However,

many of these challenges are not limitations inherent to the monetisation methods but result from the way that they are applied, and different approaches have been proposed for addressing the above challenges e.g. handling equity in monetisation [1].

7 Conclusion and directions for further research

The background of this review is the trade-off that typically occurs when the increase in accessibility for motorised modes on a regional and inter-urban scale leads to a decrease in accessibility for pedestrians and cyclists on a local scale. The assessment of these barrier effects of transport infrastructure is rarely based on objective methods even though these methods do exist. The possible reasons that are mentioned for this lack is that the problem of barrier effects is complex, it is difficult to separate barrier effects from other impacts and, the dissemination of the literature on barrier effects is limited. In response to these problems, the goal of this article is to increase the knowledge base concerning barrier effects, which can offer support for practice and research for objective assessments of barrier effects.

7.1 Contributions to practice and theory

Based on a broad literature review, we have proposed a conceptual model for barrier effects of transport infrastructure and traffic (Fig. 1) that defines the relationships between the determinants of barrier effects and distinguishes different levels of barrier effects. The determinants of barrier effects are identified as 'Transport features', 'Crossing facilities and routes', 'People's abilities', 'Land use' and 'People's needs'; the effects of barriers are categorised in three levels as 'Direct effects', 'Indirect effects', and 'Wider effects'. Importantly, since effects can influence the determinants, which in turn may create new barrier effects, the two parts of the model may interact in a feedback loop. The model offers the possibility of quickly obtaining an overview of which elements in a given situation need to be taken into consideration when assessing barrier effects.

The review highlights how barrier effects are the result of a chain of events involving characteristics of transport systems, of the built environment, and of people. As a consequence, we conclude that barrier effects cannot be treated as a singular externality of transport but instead require a multidisciplinary approach. A central condition for the collaboration in this multidisciplinary approach is consensus about how different elements and aspects of barrier effects are to be named, and how they relate to each other. The proposed conceptual model can contribute to this collaboration by identifying and relating the different determinants of

Table 10 Techniques for monetisation of barrier effects

Technique	Examples	References
Estimated values	Using general estimates to assign a monetary value to a barrier effect	Flowerdew and Hammond [49], Monzon et al. [106]
Contingent valuation method (measuring Willingness To Pay (WTP) for non-market goods using bidding techniques)	Measuring WTP for avoiding a motorway	Grudemo [55], Soguel [128]
	Measuring WTP for avoiding a barrier to a recreation area	Grudemo et al. [56]
Choice modelling (measuring preferences or WTP based on choice experiments involving different combinations of characteristics of a barrier)	Measuring WTP for reducing barrier effects of different types of roads, involving characteristics related to road design, traffic intensity and crossing facilities	Anciaes and Jones [10]
	Measuring WTP for reducing barrier effects of roads	Anciaes et al. [6]
	Measuring WTP for removing a barrier between two neighbourhoods, taking into consideration amenity characteristics	Grisolía et al. [54]
	Measuring Willingness To Accept a new road that reduces access to a recreational area, using increased leisure time as a result of decreased travel time as a payment vehicle	Ivehammar [72]
Hedonic modelling (measuring WTP for different attributes of housing (e.g. view, distance to station) based on analysis of house sales)	The impacts on WTP for housing related to reductions in accessibility caused by a motorway	Broach et al. [33], Eliasson et al. [45], Ellis [46]
Objective valuations (using the value of related market goods as proxy for the cost of barrier effects)	Socio-economic costs (increase in traffic accidents, travel time, school transport, sick leave, parking costs etc.) when potential bicycle links are not realised due to barriers	Sælensminde [124]
	Time spent accompanying children to school	Tate and Mara [129]
	Monetisation of delay	Baart and Molenkamp [15], Jarlebring et al. [74]
	Multiplying the total population by the number of seconds of delay that roads and motorways imply. The resulting time is multiplied by a monetary value	van Essen et al. [139]
	Demand for crossing facilities as a decreasing function of the generalised cost of crossing (such as time to reach the crossing facility, effort of crossing)	Héran [67]

barrier effects in a non-hierarchical way. The model describes how barrier effects can be created by a transport feature and can be multiplied by both the distribution of land use over both sides of the feature as well as by the needs of people to access these land uses. The categorisation of barrier effects in direct, indirect and wider effects can further facilitate this collaboration by highlighting the different roles of different actors in the assessment process.

Further, the literature review has found a number of tools for the assessment of barrier effects, and using the conceptual model these tools were categorised and linked to the different levels of barrier effects that they address. This makes it possible to decide more quickly for which project scale and phase and for which assessment question the different indicators are most relevant. Indicators in the categories Crossing effort (dynamic characteristics) and Passing effort (Table 8) for instance, are not relevant to the assessment of a railway project.

The conceptual model and the listed indicators and methods can facilitate objective assessment of barrier

effects, which in turn can enable the engagement of stakeholders such as local communities, who often lack access to the technical competence required to interpret indirect and wider barrier effects. Additionally, a multi-disciplinary and more inclusive approach increases the likeliness that measurements to mitigate barrier effects fulfil their purpose.

7.2 Further research

The article opens up several directions for potential further research. First, there is a need to extend the evidence base for barrier effects, as only seven of the twelve direct and indirect barrier effects identified in this review are supported with empirical evidence, and the majority of these studies relates to single cases. Second, further work remains regarding the development of indicators in order to cover all types of barrier effects and allow the assessment of not only the magnitude but also of the significance of barrier effects, which is the point when an effect turns into an impact.

Thirdly, in this article, we have limited the description of wider barrier effects to what has been presented in

the reviewed literature. But many of these effects relate to topics, such as segregation and urban development, that have been studied extensively by other sciences, for example social sciences. A third direction of research is then, on the one hand, to relate the insights offered in those fields of research to the theories and tools of barrier effects, and on the other, to introduce the case of infrastructural barriers into these fields. The conceptual model offers a framework for enabling these inter-disciplinary research exchanges.

The fourth direction concerns the application of the indicators in practice. Transport infrastructure involves a wide range of construction types, project phases and geographical scales, from national high-speed railways to a pedestrian bridge across a road. Anciaes et al. [8] proposed a scheme how to relate these to different types of techniques and methods for the assessment of barrier effects. Further research is needed to establish how the indicators presented in the current review can be categorised in this or another suitable scheme, which can offer explicit guidance for their use in practice.

Fifthly, due to its multi-faceted character, the assessment of barrier effects can involve a multitude of analyses, which can lead to problems of readability, interpretation fatigue, and loss of overview. Further research is needed to establish how the diversity of analyses can be aggregated into comprehensible and concise decision support.

Sixthly, in the introduction we argue that the current practice of basing assessment of barrier effects on subjective descriptions can have a negative impact on the levels of trust between stakeholders. It would be valuable to study what the model and the indicators can contribute to these collaboration processes, specifically if the objective decision support that they offer can increase levels of trust between stakeholders.

Finally, we also see some theoretical implications emerging from the relation between accessibility and the conceptual model of barrier effects, which cannot be fully developed here. The five determinants of barrier effects in the conceptual model developed in this study can be aligned with the three main elements of accessibility [53]: first, 'People's abilities' and 'Peoples needs' concern the individuals that are 'Agents' in the model of accessibility; second, 'Land use' relates to the different kinds of 'Attractions' that agents want or need to access; third, 'Transport features' and 'Crossing facilities and routes' represent the 'Impedances' that agents need to overcome to access those attractions. Framed this way, the concept of barrier effects can to some extent be said to describe the inverse of accessibility, in dealing with the *effort* of reaching, rather than the *ease* of reaching, as accessibility is described (Cervero 1996, in: [94]). In

these terms, the improvement of car infrastructure can be described as commonly being aimed at decreasing the impedance (travel time) for the agents (car drivers) to access certain attractions, and increasing car accessibility. This infrastructure often introduces a barrier in accessibility systems on a local scale, increasing impedance for other modes, for instance walking, to access attractions. Since the general aim for national transport administrations concerns the optimisation of accessibility for all members in society, it is essential to understand the way accessibility works as an inter-scalar system, where the optimisation of accessibility on one scale can lead to a sub-optimal outcome for another. There is a need for research to capture this interaction, which we hope to have contributed to. With adequate theoretical support, investments in transport infrastructure can be based on broader decision support involving not only the benefits of increasing remote accessibility but also the costs of reducing local accessibility.

Authors' contributions

JE has performed the literature review on which the manuscript is based and has written the larger part of the text. JG and LM have supervised the research, contributed to the structure, conceptualization, and reviewed the text. All authors have read and approved the final manuscript.

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Declarations

Competing interests

The authors declare that they have no competing interests.

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