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Missing links – Quantifying barrier effects of transport infrastructure on local accessibility

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ABSTRACT

Transport infrastructure can create efficient connections in traffic systems, yet it can also create barriers to movement on a local scale. In transport infrastructure projects there is a need for methods to quantify these barrier effects – also called severance – to assess their impacts on social inclusion, health and viability of businesses.

This paper proposes four local accessibility indicators to measure direct barrier effects: Travel time, Choice, Catchment and Service efficiency. The indicators are tested in a case study where the consequences of placing a motorway and a railway in tunnels are assessed. The results show how local accessibility is affected in non-linear patterns.

The paper contributes to accessibility literature by introducing direct barrier effects as an applied case of local accessibility, and demonstrates the potential of those indicators to quantify barrier effects. Finally, it offers accessibility as a theoretical framework for further developing theories on barrier effects.

1. Introduction

Cities can be understood as distributions of accessibility. One of the elements that have a fundamental influence on this distribution is transport infrastructure, which can create efficient, conflict-free connections between city districts, regions and countries, but it can also create barriers to movement on a local scale. Through an intricate process of cause and effect, these barriers can have a series of negative consequences on the potential for social contacts within neighbourhoods (Bradbury et al., 2007), between neighbourhoods (Anciães, 2013), on access to facilities (Clark et al., 1991) and to workplaces (Anciães, 2011), on the conditions for economic viability of businesses (Forkenbrock and Weisbrod, 2001; Jacobs, 1961), on health (Mindell and Karlsen, 2012), and on possibilities for urban expansion (Korner, 1979). Thus, an overall increase in regional accessibility is often achieved at the expense of a drop in local accessibility for specific population groups and to specific services.

Decisions concerning investment in infrastructure projects are usually based on extensive assessments of their effects. For many of these effects, such as noise and pollution, quantitative and objective ways of measuring have been developed. As a result, specific regulations with thresholds are put in place, which create restrictions for projects, with economic and legal sanctions if not complied with. However, assessments of barrier effects are usually based on qualitative and subjective estimations (Anciães et al., 2016) in the form of “a few well-chosen words” (Tate and Mara, 1997, p227). This limits the possibility of including barrier effects in the overall

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evaluation of effects, and creates the risk that these important negative impacts of investments in transport infrastructure are undervalued or disregarded.

By bridging the field of research on barrier effects and of accessibility, the present research aims to develop a simple method for the quantification of barrier effects of motorways and railways that can be used in the planning processes of transport infrastructure projects. Barrier effects can be conceptualised as the interplay between transport, land use and people (Korner, 1979). Direct barrier effects are the impacts created by transport infrastructure on physical access to activities for people, and opportunities for business. The concept of accessibility and its measurement seems to offer a unifying framework to both conceptualise and quantify direct barrier effects. In this article, a case study is presented, in which four local accessibility indicators are tested that have been developed to quantify direct barrier effects of transport infrastructure.

The article has the following structure. First, the theoretical background is presented, summarising a survey of technical reports, handbooks, academic studies concerning barrier effects and the current methods of measuring these, and second, how accessibility literature offers a platform for quantifying direct barrier effects. Next, four local accessibility indicators of direct barrier effects are introduced and defined. The next section describes the case study, the datasets, and the methods used for testing the proposed indicators. This is followed by a presentation of the results of the analyses. In the discussion section we reflect on the results and the potential use of the indicators in practice, and identify some limitations of the present study. In the concluding section, the findings are summarised.

2. Theoretical background

In this section, the relevant literature relating to barrier effects and their measurement, and their relation to accessibility measures is presented, which forms the theoretical background of this research.

In the literature, barrier effects of motorised traffic and transport infrastructure are often referred to as ‘severance’. The concept of severance presupposes the presence of a built environment or social community prior to the process in which the construction of infrastructure or the increase in traffic levels creates a barrier (Handy, 2003). However, in many transport infrastructure projects, there is no pre-existing urban area or community to sever. Additionally, urban redevelopment projects address situations where an existing infrastructure such as a motorway or railway already forms a barrier. Taking this into account, the term ‘barrier effects’ appears to be more suitable for the type of assessment method that we present in this study, and is the term used henceforth.

2.1. Barrier effects of transport infrastructure projects

A central starting point for the study is that barrier effects do not originate as an autonomous externality of a system, with a unit of measure of itself, like noise and pollution. Korner (1979) describes three situations in which barrier effects can arise: 1) changes in crossability, due to the construction of new infrastructure or to changes in design, or in traffic flow within the existing infrastructure; 2) changes in the ability to cross - this relates to demographic changes, such as an increase in the number of older people or children; 3) changes in the need to cross, due to the establishment of new destinations, the removal of existing destinations, or a change in the attractiveness of existing destinations.

Based on this description, barrier effects can be characterised as the result of the meeting of the properties of the transport system, the capabilities and preferences of people, and the properties of the land use system (Anciães et al., 2014; Geurs et al., 2009; Korner, 1979). The transport system includes features that form a barrier, namely, static properties such as walls and fences along motorways and railways, and dynamic properties like the flow and speed of traffic, but also the properties of the local street network in which the barrier is located. A motorway is not a barrier if there are sufficient cross-connections in the local network.

Another characteristic of barrier effects is that they can be conceived of as a chain of effects. Many descriptions of the complex causal pathway between barriers and their wider consequences for individuals and groups have been proposed (Anciães et al., 2016; Geurs et al., 2009; Korner, 1979; Marsh and Watts, 2012; Mouette and Waisman, 2004). As the present research aims to develop a method for the assessment of barrier effects for use in infrastructure planning processes, the scheme by Korner (1979) is particularly suitable. Korner arranges barrier effects into three hierarchical, consecutive levels: 1) primary effects: the direct effects of the barrier, such as loss of time and detours; 2) secondary effects: changes in travel behaviour which are caused by those primary barrier effects, such as frequency of visits, choice of destinations, mode of transport or route; 3) tertiary effects: the further consequences for society as a result of the changes in travel behaviour, for instance, liveability of streets, social interactions, commuting patterns and health. In this article, we will refer to these three levels as direct, indirect and wider effects, terms that are more commonly used within the field of transportation.

In the present study, the focus is on direct effects only, as these generally are directly related to investments in transportation infrastructure and can be more easily understood and isolated. Indirect and wider barrier effects are the subjects of other assessments in the transportation planning process, such as child impact assessments, social impact assessment and traffic assessments, and are, as such, not covered in this paper.

At the core of direct barrier effects are the increase in travel time, distance, cost and effort that a barrier can cause, along with reduced access to facilities such as education, health care, services, public transport stops, and leisure (Korner, 1979; Clark et al., 1991; Bradbury et al., 2007). Further, both choice of facilities available to people and catchment areas of facilities can be reduced (Bradbury et al., 2007; Clark et al., 1991; Korner, 1979). Accessibility to workplaces can be affected when the infrastructure, as barrier, limits communication (Anciães, 2011), but can also, as improved connection, increase access (Nimegeer et al., 2018). A further direct effect is the reduction in service efficiency of services such as freight, mail, waste collection, public transport, and emergency services (Cline, 1963; Héran, 2011).

In order for these direct barrier effects of transport infrastructure projects to be taken into account in practice, methods to quantify them are required.

2.2. Methods for quantification of barrier effects

Most of the literature on barrier effects proposes, alongside a definition and description, a method for their quantification. One of the earliest methods for assessing barrier effects was presented by the Swedish Transport Administration, Trafikverket, (introduced by Reyier, 1987 and revisited by Jarlebring et al., 2002). The method begins with calculating the magnitude of a barrier based on traffic flow, speed, and the number of trucks. Anciães et al. (2014) state that some consensus appears to exist concerning these parameters of how to define a barrier. The Trafikverket method then continues with measuring how local trips by residents are affected by a barrier, using statistics on the local travel behaviour of residents of different age groups. The extra travel time imposed by the barrier on these local trips is monetized.

One limitation of this method is that it does not consider the role of the spatial distribution of destinations, i.e. land use, and of the local street network (transport) in the extent and spatial distribution of barrier effects. Another limitation is that the consequences of barrier effects are too complex to be measured by the sole indicator of extra travel time (Quigley and Thornley, 2011). Hine remarks that a "key weakness of delay measures, treated in isolation, is that they do not refer to the deterrence of road crossings, that is, to those pedestrians who do not cross" (Hine, 1994, p. 14). A further limitation of the method is that it can only measure the delays involving crossing streets and roads at level crossings, which renders the method not applicable to motorways and railways where crossing is only possible by separating traffic flows. Indeed, the method was not used in any of the 70 assessments of infrastructure planning projects in Sweden that were reviewed for the present research. After interviews with experts at Trafikverket, the only projects that could be found where the method was tested, were two road projects, Väg 19 Förbi Degeberga (2002) and E22 Förbi Linderöd (2002). However, in the final assessments of these two projects, the results of the barrier assessments were not used (Trafikverket, 2016, 2007).

A quantification method taking spatial structure and distribution of land use into consideration was by developed by Clark et al (1991) for the British Department for Transport. This method quantifies barrier effects by estimating the number of residents for whom access to facilities is affected. Here, facilities are identified, the catchment areas for these facilities are drawn up, and the number of residents is estimated - both the total number of residents and separately the number of persons who may be considered especially vulnerable to barriers, such as older people, children, people with a disability, and people who are highly dependent on their community ties. A limitation of this method is that it describes barrier effects from the perspective of facilities only.

Forkenbrock and Weisbrod (2001) suggest that besides changes in travel time and travel costs, effects on accessibility could be measured by changes in the number of choices of destinations that are available to residents within a given travel time. Furthermore, the reduction in service efficiency for service transports has been pointed out as a barrier effect by Cline (1963).

Mindell et al. (2017) developed a set of tools for the quantification of barrier effects of busy roads. The tools measure the monetary cost of the barrier, based on Stated Preference (SP) methods. For barriers created by transportation infrastructure such as motorways and railways, being static and absolute, these tools cannot be applied. Grisolía et al. (2015) do deal with absolute barriers in a SP study in which they measure the Willingness To Pay of residents for placing a motorway in a tunnel. This study, like Mindell et al. (2017), focuses on the role of the infrastructure, but does not address the role of land use nor of the local street network in to what extent, and where, barrier effects arise.

Anciães and Jones (2020) have developed a method for valuing barrier effects in which they combine SP as well as Revealed Preference methods. This method takes aspects of the local street network and distribution of destinations into consideration, but only in regard to individual trips as reported by those responding to the survey. Further, the method appears to relate to dynamic barriers, where the possibilities to cross vary over time, rather than absolute barriers that permanently hinder cross connections.

In his study of the barrier effects of motorways, Anciães (2013) proposes 'walking distance to facilities' as an indicator for what he defines as 'population-interaction potential' between neighbourhoods on either side of the motorway. With this indicator, Anciães shows how a newly constructed motorway reduces the potential for residents from different neighbourhoods to meet, compared to the situation ten years before the motorway was built. This method does consider parts of the local street network and the distribution of destinations, and forms a central reference for the present study.

2.3. Accessibility and its measurement

The above overview of methods for quantifying direct barrier effects reveals a variety of measures proposed by different authors. Each one takes a different perspective on the concept, and has certain strengths but also leaves a number of gaps. This range of perspectives reveals the scope and diversity the problem of direct barrier effects, and calls for an integrative approach in order to combine these perspectives, and to create quantification methods that are consistent and useful for practice. A well-established unifying framework that is able to conceptualise and operationalize barrier effects can be found in accessibility and its measurement.

According to Handy and Niemeier (1997), accessibility to jobs, services and friends is the reason why people live in cities – despite congestion, high housing costs and crime. Barrier effects, by definition, can negatively affect all these qualities; hence the two concepts of accessibility and barrier effects are intrinsically linked. The three elements of barrier effects (namely, transport and traffic, land use, and people) are components of accessibility, and are mentioned by a number of authors. For example, Geurs and van Wee (2004) identify four components of accessibility: land use; transport; temporal; individual. Ferreira and Batey (2007) identify five layers of accessibility: transport networks; supply and demand; temporal; perception; institutions and culture. Beyond this conceptual alignment, accessibility can offer an operational framework for the quantitative measurement of these effects in transportation infrastructure planning projects.

Over the past two decades, a shift in transportation infrastructure planning has taken place, from a focus on mobility, i.e. the efficient movement of people and goods as a dominant performance metric and supporting motorways that promise high capacity and high speeds, to an increasing concern about accessibility (Levine et al., 2019; Straatemeier, 2008). This shift from mobility to accessibility involves adding land use in the assessments of transport projects similar to what Korner (1979) proposes in order to assess the barrier effects of those projects. As Levine et al (2012) have shown, the focus on mobility in transportation projects can lead to a reduction in accessibility as it fosters dispersed, low density land use. In recent years, national and regional transportation agencies, such as Trafikverket in Sweden, have regarded accessibility as a central policy goal (Trafikanalys, 2012). Likewise, Transport for London has developed accessibility instruments to assess the performance of the public transport system (Inayathusein and Cooper, 2018).

According to Papa et al. (2015, p57) “Accessibility instruments are a type of planning support system (PSS) designed to support integrated land use transport analysis and planning through providing explicit knowledge of the accessibility of land uses by different modes of transport at various geographical scales.” There are numerous examples of the application of accessibility instruments in transportation planning projects, but it is beyond the scope of this article to offer a comprehensive review. These are frequently used to assess and compare the accessibility of public transport projects against dominant car travel (Benenson et al., 2017, 2011; Karou and Hull, 2014) at metropolitan and regional scales.

While these types of studies support important strategic urban development goals, it is recognised that accessibility instruments need a stronger focus on local accessibility indicators (Silva and Larsson, 2018), especially in relation to transport infrastructure projects designed to improve regional accessibility. It is also necessary to provide support in the decision processes at the local scale, so as to avoid a situation where an increase in regional accessibility to jobs leads to a decrease in local accessibility. McCahill (2018) offers an example of local accessibility analysis with a focus on a diverse range of trip purposes beyond travel to work. In this respect, the assessment of direct barrier effects of transportation infrastructure projects can offer a practical context for the application of local accessibility instruments.

To summarise, accessibility instruments have a conceptual foundation that is compatible with the definitions of barrier effects, and they are well established in the quantitative measurement of transportation and land use planning projects. Local accessibility indicators can therefore offer a basis for developing an integrated set of direct barrier effect indicators, while the assessment of barrier effects offers a practical opportunity of further establishing local accessibility instruments in the transport infrastructure planning processes.

3. Local accessibility indicators of direct barrier effects

Drawing from the theoretical background, four local accessibility indicators were developed to quantify direct barrier effects: Travel time, Choice, Catchment, and Service efficiency. The indicators and their general definitions are presented in Table 1.

From an accessibility perspective (Papa et al., 2015), the indicators can be classified as spatial separation measures (Travel time and Service efficiency) and cumulative measures (Choice and Catchment). Further, the indicators consider three of the four components of accessibility as defined by Geurs and van Wee (2004): land use, transportation and the individual.

The indicators measure the local impacts of infrastructure on some of the conditions for the daily lives of the people living in the vicinity of the infrastructure. Although the focus in the present study is on pedestrian and bicycle travel, the indicators are based on general accessibility measures and are not to be considered as specific pedestrian and cyclist indicators. Rather, the parameters for each indicator (i.e. travel time budget, speed, network and facilities) can be adapted for each social group, their travel mode, and for the particular infrastructure project that is assessed. In the proposed indicators, travel time and distance are measured along the street networks, to capture small variations in local effects. Time can, in its simplest form, be calculated as a factor of distance and the average speed pertaining to a mode of travel. However, in direct barrier effects travel time can also include more detailed, non-distance-based delays, such as crossings, stairs, or traffic lights.

Table 1

Proposed direct barrier effects indicators and the measurements for their quantification.

Direct barrier effect	Indicator	Measurement	Accessibility measure
Increased travel time and distance	Travel time	Travel time from each location to the closest destination in a category.	Spatial separation
Reduction in available choices of destinations	Choice	Number of destinations in a category within a fixed travel time from each location.	Cumulative opportunities
Reduction in catchment areas for facilities	Catchment	Number of households within a fixed travel time from each facility.	Cumulative opportunities
Reduction in service efficiency	Service efficiency	Duration of public service vehicles trips (e.g. ambulances, public transport, waste collection, etc.) between public facilities and each location.	Spatial separation

3.1. Travel time

The travel time indicator refers to the effect of barriers on people's access to destinations (Clark et al., 1991; Korner, 1979; Vigar, 1999). The indicator measures the travel time $T(i)$in minutes between a location i and the closest point j in a given category of destinations using (1)

$$T(i) = \min_{j \in A} N(i, j) \tag{1}$$

where

A = a set of destinations in a category
$N(i, j)$ = shortest travel time from origin i to destination j.
i = origin location
j = point in a set of destinations

In order to capture the effect of a barrier, the situation before and after the realisation of the proposed infrastructure needs to be compared. Or, if the project involves an alteration in infrastructure, the modified and existing situations need to be compared. For Travel time, the percentage change of Travel time between the two situations is calculated.

3.2. Choice

Choice measures the number of destinations that are accessible from a location (Forkenbrock and Weisbrod, 2001; Wachs and Kumagai, 1973). Choice of destinations Chavailable to a location i within a given fixed travel time in minutes t is calculated using (2)

$$Ch(i) = \sum_{j \in A} N(i, j) \tag{2}$$

where

t = a given fixed travel time
A = the set of destinations in a category, reachable within a fixed travel time from i
$N(i, j)$ = shortest travel time from origin i to destination j
i = origin location
j = point in a set of destinations

The percentage change of Choice between the before and after situations is calculated.

3.3. Catchment

The indicator Catchment, based on the method proposed by Clark et al. (1991), measures the number of households accessible within a given travel time. It describes barrier effects in the same way as Choice but here from the perspective of each facility. Typically, categories of facilities are selected that compete in a common market, and for which travel time constitutes a factor that determines people's choices. Catchment Ca for a facility i is calculated using (3)

$$Ca(i) = \sum_{j \in A} N(i, j) \tag{3}$$

where

A = the set of households, reachable within a fixed travel time from facility i
$N(i,j)$ = shortest travel time from facility i to household j
i = origin facility
j = point in a set of households

The percentage change of Catchment between the before and after situations is calculated.

3.4. Service efficiency

The indicator Service efficiency refers to the reduction in efficiency of public services as described by Cline (1963) and Héran (2011). This indicator measures the effects of a barrier on accessibility to transportation-based public services (such as ambulances, public transport, waste collection) for residents and visitors in the vicinity of the barrier. For this indicator to capture the level of service provided at specific locations on the street network, the total travel time is calculated for journeys between the public service facilities from which the different vehicles depart (such as the ambulance central) and the facilities where they eventually arrive (the hospital emergency department) via the target locations on the street network. For the analysis, the shortest travel time in minutes S_f

(i) between location *i* and the public facility *j* of a specific type *f* (closest to *i*) is calculated using (4). The sum of $S_f(i)$ for all facility types of a given service is calculated as total travel time *SE(i)* for each target location *i* using (5).

$$S_f(i) = \min_{a \in A_f} N(i, j) \tag{4}$$

where

A = the set of public facilities (of a given type f)
f = the type of public facility (point of departure or arrival of a given service)
N(i, j) = shortest travel time from location i to public facility j
i = origin location
j = point in a set of public facilities

$$SE(i) = \sum\nolimits_{f=1}^{n} S_f(i) \tag{5}$$

where

$SE(i)$ = travel time between i and closest public facility of type f
i = origin location
f = the type of public facility (departure or arrival of a given service)

The absolute change of Service efficiency between the before and after situations is calculated.

4. Case study and methods

In this section the case study is introduced, that was selected to test and demonstrate how the direct barrier effect indicators can be applied to a transport infrastructure project. Additionally, it presents a description of the Geographic Information System (GIS) models, including the data sets and tools for calculating the direct barrier effect indicators.

In the analyses, the focus is on pedestrian and bicycle traffic as these modes are affected the most by barriers. Furthermore, the political goals that have been formulated for Trafikverket (Trafikanalys, 2012) mention explicitly that infrastructure projects need to improve conditions for these modes, that the contribution to climate change by the traffic system should be reduced, and that the traffic system should contribute to improved health.

4.1. Case study

The case study is located in the north of Gothenburg, Sweden, where a four-lane motorway, Lundbyleden, and a railway track, Hamnbanan, impose substantial restrictions on the urban redevelopment of a former harbour area in the centre of the city and the surrounding areas in general. The case illustrates how developments of land use can play a role in transforming an existing infrastructure into a barrier. When Lundbyleden and Hamnbanan were constructed in 1958 and 1914 respectively, they purposefully separated an area with shipyards and other industry from the rest of the city. But over the last decades, this area has been redeveloped into a mixed-use residential area, and the existing infrastructures have become barriers to the potential benefits of these new developments to the population at large.

The city council formulated a number of policy documents expressing the ambition to unite the city as a whole and to improve its contact with Göta Älv, the river that runs through the city (Göteborgs Stad, 2012, 2009). In 2008 Trafikverket issued a pre-study (Trafikverket, 2008) in which different planning alternatives for Lundbyleden and Hamnbanan are presented that could reduce negative effects like noise, pollution, and barriers, in the surrounding areas.

The alternative assessed in this research is to place the motorway and the railway in tunnels, because this solution offers greater potential to demonstrate the barrier effect and its reduction. The reduction in barrier effects is measured by comparing this tunnel alternative with the present situation. The analyses are performed with networks on a city-scale; however, the results presented are limited to a study area of an 800-m buffer around the location of the tunnels as proposed in the pre-study by Trafikverket (2008). The choice of the study area is based on an assumption of the size of the local neighbourhood around the barrier, and it coincides with a number of existing borders in the area around Lundyleden and Hamnbanan. Within the study area, an inventory was made of all current urban and traffic projects (see Fig. 1). Some of these projects are in the early planning stages, while others are under construction. The main developments in the study area involve Backaplan (1), Frihamnen (2), Ringön (3), Karlavagnsplatsen (4) and Volvo (5). These comprise various initiatives to densify the city with housing, retail, services and offices. North of Ringön, a tram depot (6) is currently under construction. The depot is a clear example of what Anciães describes as another element besides infrastructure, that can create strong barriers in cities (Anciães, 2011). Since the site will become just as effective a barrier as the motorway and railway already are, the project is left out of the study.

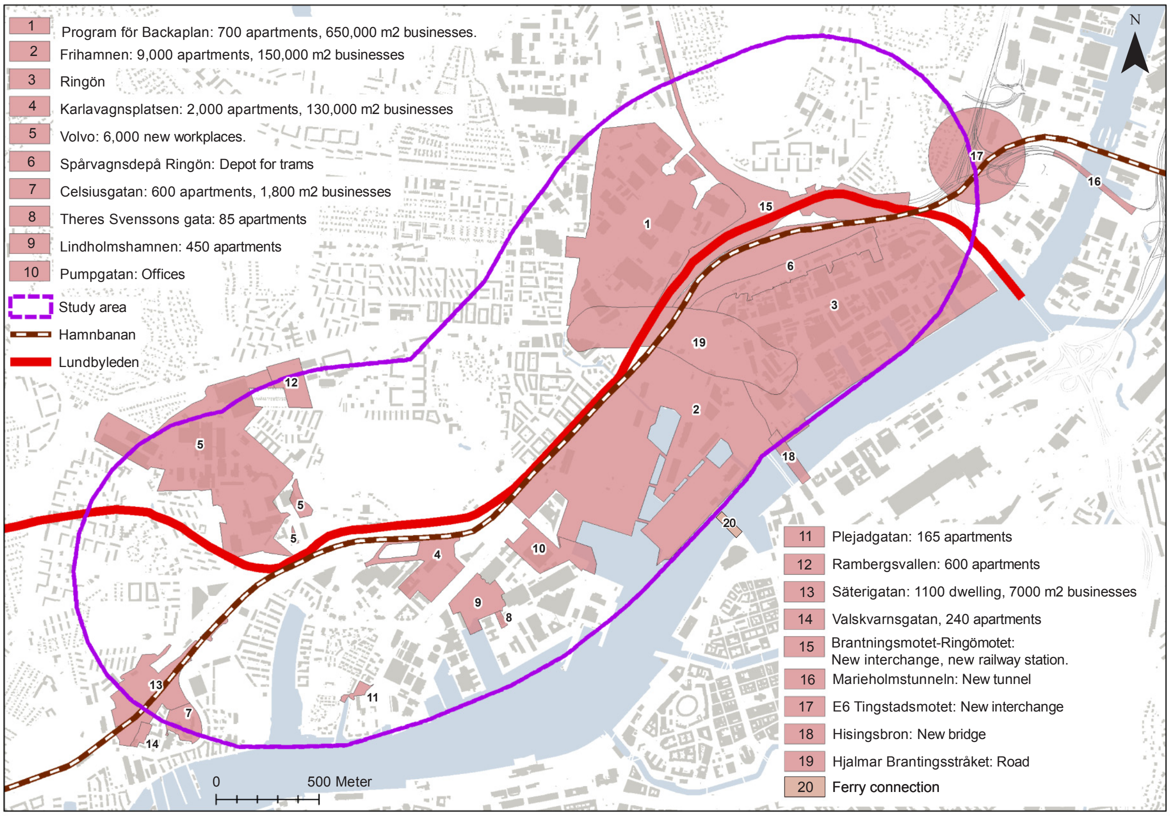

Fig. 1. Overview of study area, location of Lundbyleden and Hamnbanan, and current urban and traffic planning projects in the study area.

4.2. GIS models and datasets

In the study, two road centre line (RCL) networks of Gothenburg were used, which were developed by the Spatial Morphology Group at Chalmers (Berghauser Pont et al., 2017): one network for pedestrians and cyclists, and one for cars and heavy goods vehicles. Data sets provided by Open Street Map (OSM) and the municipality were used for data on address points and on commercial, residential and public facilities. A limitation of using OSM data is that the coverage and quality depends on the accuracy and engagement of the volunteers who create and update the data. However, the material used in the study was deemed to be of good enough quality for the purpose of demonstration. As the indicators deal with a rather uncertain situation, based on assumptions of future land use and networks, the OSM data are suitable for representing a distribution of facilities.

Facilities and other destinations were categorised in two stages. First, in 39 groups, using the Swedish Standard for Industrial Classification (SNI) (Statistics Sweden, 2007). These groups, plus destinations that fell outside of the SNI classification (such as parks and playgrounds), were then ordered according to the categories used in a travel survey by the traffic department of Gothenburg municipality (Göteborgs Stad, 2015): Work and study; Schools; Day care; Shopping; Training and recreation; Other (Table 2).

In addition to existing data, all the proposed new street and bridge/ferry connections were added to the two RCL networks of Gothenburg (Fig. 2). Further, all proposed new housing and commercial and public service projects inside the case study area (Fig. 1) were added to the GIS model. These projects encompass a total of 14,340 apartments and approximately 938,800 square m of floor space for retail, offices and services. Adding these future connections, residences and destinations allows for a more accurate assessment of the long-term barrier effects of the two scenarios.

Table 2
Categorisation of destinations based on RVU 2014 (Göteborg Stad, 2015).

RVU Category	Type of destination
Work and study	Workplaces, higher education (universities, professional)
Schools	Primary and secondary education
Day care	Pre-primary education
Shopping	Retail
Training and recreation	Sport centres, swimming pools, parks, nature areas, quays
Other	Health care, public services, commercial services, culture, restaurants, bars, leisure, religion

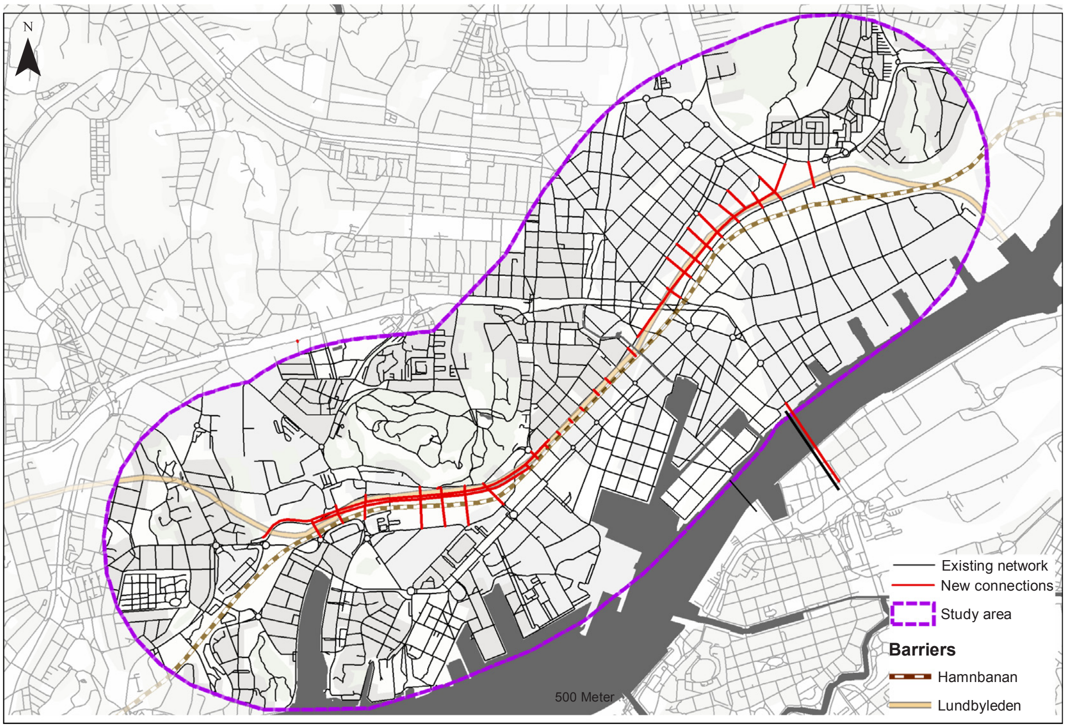

Fig. 2. The new connections in the tunnel alternative (red) in the road centre line network for pedestrian and bicycle traffic (Berghauser Pont et al., 2017).

Two versions were made of each of the two street network models, one of before, and one of after the transport infrastructure change. To model the tunnel scenario, the RCL networks were adapted: new connections were added to the existing urban structure and proposed urban development project, across the site of the motorway and railway, increasing the number of cross-connections from 8 to 36 (Fig. 2). Further, two longitudinal connections were added, representing a street located on the site of a former motorway and railway. The same datasets of locations of residences and locations of facilities and services were added to all four models. The GIS model data preparation was carried out in QGIS 2.18[2].

4.3. Indicator calculations

The four local accessibility indicators of direct barrier effects were calculated using the GIS model described above and a combination of different GIS tools, applied to two scenarios in the study area, namely the present situation and the tunnel alternative (Fig. 2). As the focus of this study is on demonstrating their potential, the indicators have not been adapted for any specific social groups, but are instead based on general assumptions of the needs, wishes and capabilities of people. While the results are reported only for the study area, that is, the 800 m buffer around the infrastructure project, the calculations take into account the complete GIS model of the city of Gothenburg. In all indicators (Sections 3.1 to 3.4), the midpoints of the street segments of the RCL network are used as locations. By using street segments instead of residential addresses, the analyses present the potential of different urban spaces, regardless of their present use. Another argument in favour of using street segments as locations, is that it includes all trips, not only those that start from home.

For the calculation of Travel time (Section 3.1), the tool Attraction Distance from the Place Syntax Tool[3]-plugin (PST) for QGIS version 2.18 was used (Marcus et al., 2019; Ståhle et al., 2005). Travel time was calculated separately for the destinations in RVU categories Schools, Day care, Shopping, and Training and recreation, using the pedestrian and cyclist RCL network.

For the calculations of Choice (Section 3.2), Attraction Reach from PST was used, taking into account the destinations within a 10-minute travel time frame by bicycle from each origin, which is considered to be a typical cycling time. Choice was calculated separately for the destinations in RVU categories Schools, Day care, Shopping, and Training and recreation, using the pedestrian and cyclist RCL network.

For the calculations of Catchment (Section 3.3), Attraction Reach was used, taking into account households within a 10-minute travel time by bicycle from each facility. Catchment was calculated for the facilities of type Day care centres, fast food restaurants,

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[2] https://www.qgis.org/en/site/.

[3] https://www.smog.chalmers.se/pst.

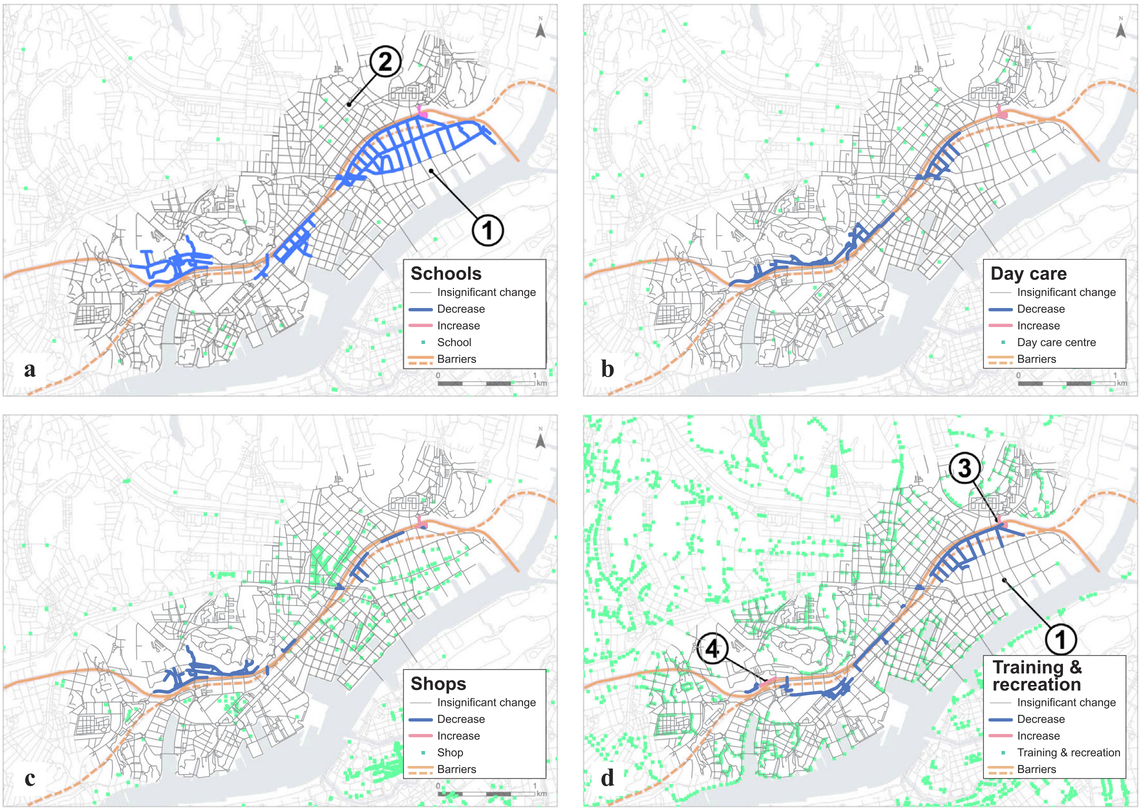

Fig. 3. Change in travel time between street segments and destinations in the tunnel alternative. For blue segments the travel time decreases, for pink segments it increases, and for grey segments there is no significant change. (1) Ringön; (2) Backaplan; (3) & (4) street segments where travel time to destinations increases due to changes in street layout following the tunnel construction.

sport centres and playgrounds, using the pedestrian and cyclist RCL network.

In the calculation of Service efficiency (Section 3.4) the RCL network for cars and trucks is used, instead of the pedestrian and cyclist network. In this indicator, the travel time of health emergency services is calculated as an example, using the ambulance stations as departure facilities and the hospital emergency departments as arrival facilities. Also, for the calculation of Service efficiency, Attraction Reach was used.

5. Results

In this section, the results of applying the four indicators described in Section 3 to the tunnel scenario (Fig. 2) are presented in a series of maps.

5.1. *Change in travel time*

Travel time to Shops (Fig. 3c) and to Day care (Fig. 3b) destinations are the least affected by the barriers as there are many such destinations spread relatively evenly across the whole city. Therefore, effects on travel time to these destinations are concentrated in areas in the direct vicinity of the barriers. Schools (Fig. 3a) are an exception, as there are fewer schools overall and none are planned for Ringön (1). Therefore, travel time to these destinations increases significantly when new streets connect the north of Ringön to Backaplan (2) where four new schools are planned. Also, there are few Training and recreation destinations (Fig. 3d) in Ringön (1), which leads to an increase in travel time in a greater number of segments.

Some street segments have longer travel times to destinations in the tunnel alternative due to the fact that these segments disappear in the tunnel alternative. Connection 3 (in Fig. 3d) would be removed in the reconstruction of an interchange when the tunnels are constructed, and connection 4 in Fig. 3d) would disappear when the motorway is replaced by a street grid.

5.2. *Change in Choice*

The analyses of Choice show substantial differences between different destination categories and, further, that the increase in Choice does not necessarily only occur close to the barrier. Some results can be highlighted. In Backa (1), tunnels would increase

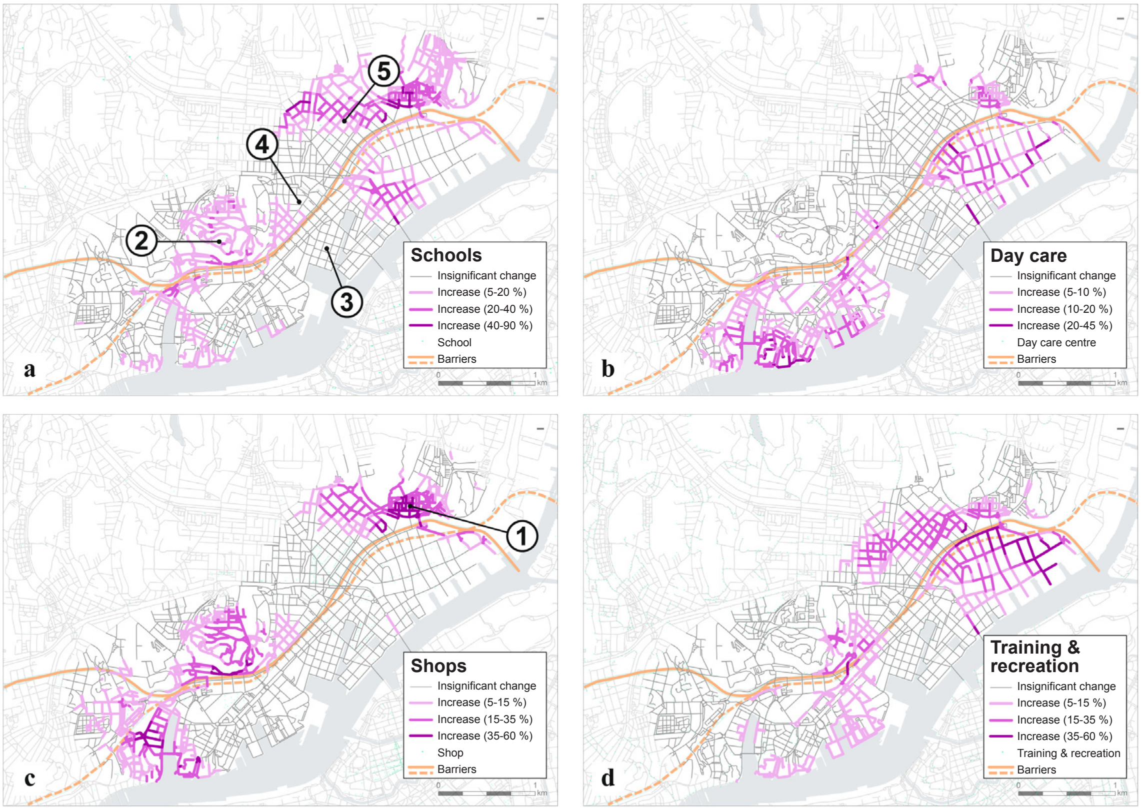

Fig. 4. Change in Choice of the number of destinations within a fixed travel time of 10 min by bicycle around each street segment. Purple to grey indicate increase in Choice in percent; for grey segments there is only minor change. (1) Backa; (2) Ramberget; (3) Frihamnen; (4) Kvillestaden; (5) Backaplan.

Choice of shops within a fixed travel time of 10 min by bicycle by as much as 60% (Fig. 4c). Backa has a high increase of Choice for all destination categories except Day care (Fig. 4b) and Training and recreation (Fig. 4d). Choice of Schools (Fig. 4a) and Shops (Fig. 4c) increases for Ramberget (2) too. It is important to know that this area is a park located on a hill with few destinations other than Training and recreation.

Another interesting result is that Frihamnen (3), Kvillestaden (4) and the southern part of Backaplan (5) show only insignificant changes in Choice for all destination categories. Although the impact that Lundbyleden and Hamnbanan have on these areas is the subject of much attention in the current planning process, it appears that this does not affect the Choice of the categories of destinations that are studied here.

5.3. Change in Catchment

The catchment area indicator describes changes in conditions for commercial and public facilities regarding, for example, economic feasibility. The analyses demonstrate that the removal of the barriers would greatly affect the catchment areas of the selected facility types, especially in Lindholmen (1) where the number of households that fall within a catchment area of a fixed travel time of 10 min by bicycle increases by 10–15% for all four categories of facilities (Fig. 5) Lindholmen is quite isolated from the rest of the city, with the river Göta to the south, harbours to the west and east, and parallel to this there are at present only six connections with the surrounding area. Again, the catchment areas of facilities located in Backaplan (2) and Frihamnen (3) show only minor increases due to the removal of the barriers.

5.4. Change in service efficiency

The Service efficiency analyses show that removing the barriers leads to a decrease in trip times for ambulances for the whole of the western part of the study area (Fig. 6). Based on an average speed of 50 km/h, this decrease can be as much as 1.92 min in Lindholmen (1). This could imply a considerable time reduction, since a reduction of 1.92 min in travelling through the city also reduces the risk of delays due to traffic congestion. Even a reduction in response time of ambulances of only a few minutes can have considerable impact on the chance of surviving a cardiac arrest, as a German study shows (Bürger et al., 2018).

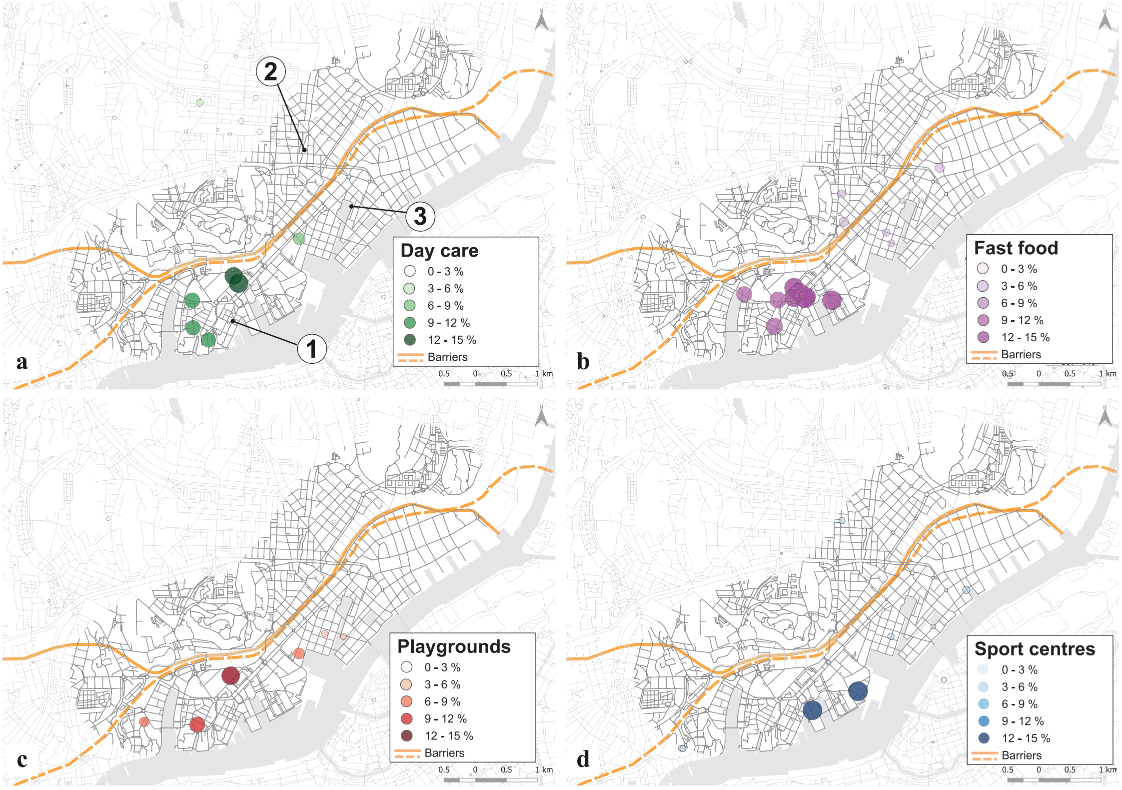

Fig. 5. Change in Catchment, showing the increase of households that fall within the catchment area around each facility (fixed travel time 10 min by bicycle).

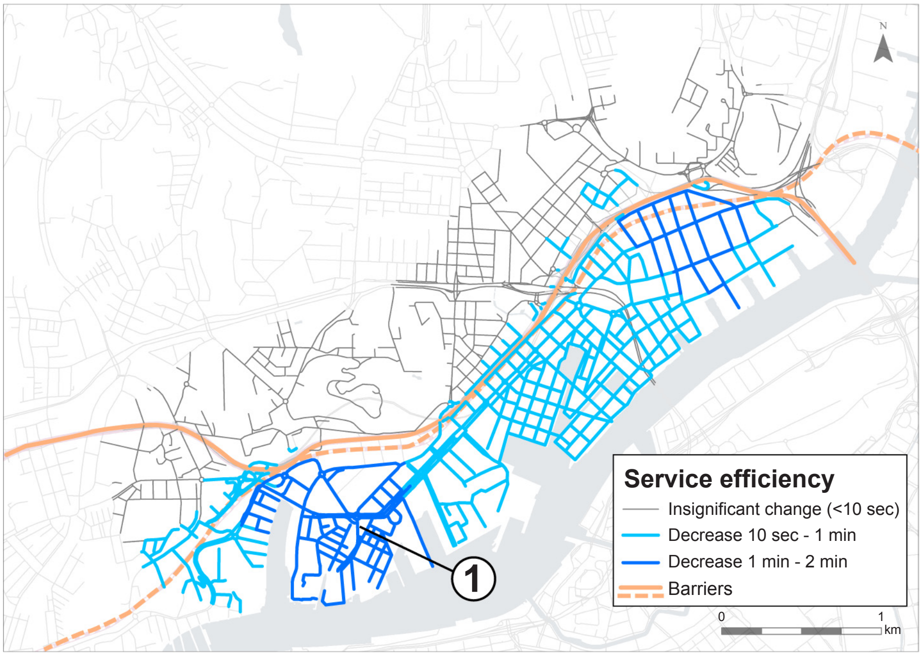

Fig. 6. Change in Service efficiency for ambulance transports. Decrease in blue, insignificant changes (< 10 sec) in grey.

6. Discussion

The results presented in this paper demonstrate the potential of the proposed local accessibility indicators to quantify the levels of direct barrier effects and their spatial distribution. The results show how these effects can be unevenly distributed rather than spread in a linear way along and from the barriers outward. This demonstrates that the indicators have the potential to offer useful information concerning the mapping of the distribution of direct barrier effects – information that cannot be obtained through aggregate calculations of average travel times between the origins and destinations of a study area. This uneven spatial distribution of barrier effects can be observed, for instance, in the central urban area around Backaplan and Frihamnen (for instance, see Fig. 4a at (3) and (4)), where barrier effects do not appear to be as extensive as expected. These results can offer useful information for the planning process of an urban area, and allow an objective assessment of the types of, and exact locations of, the different barrier effects of the transportation infrastructure.

The proposed barrier effect indicators aim to meet the criteria defined by Geurs and Van Wee (2004) for accessibility measures, stating that they should consider four components: land use, transportation, temporal, individual; should be easy to use; should be easy to understand; should show social and economic opportunities for individuals; and should show economic effects. Looking at the proposed indicators, we can observe that they take three of the four components into consideration (see Section 3). The temporal and individual component will be the subject of further research within this project. Analysis of the social and economic opportunities for individuals will require tailoring the indicators to different social groups, while further valuation of the social and economic impacts of these opportunities for individuals will require further research. The ease of use and of understanding of the indicators will require further assessment, but some first considerations on their usage are pointed out below.

In the development of the indicators, the aim has been to cover all the direct barrier effects identified in the literature: increased travel time (Section 3.1), reduction in available choice of destinations (Section 3.2); reduction in catchment areas for facilities (Section 3.3); reduction in service efficiency (Section 3.4). The indicators can also be used as input for a range of assessments of indirect and wider barrier effects, such as child impact assessments, social impact assessments and traffic assessments, offering the quantification of relevant aspects that at present are difficult to measure in a precise way (Forkenbrock et al., 2001). The indicator Travel time, for instance, measures one of the basic factors of accessibility that is fundamental for modal choice, an indirect barrier effect. Modal choice in turn is a key metric for a range of wider effects of barriers such as emission levels and health (Mindell and Karlsen, 2012). The indicator Choice can be used to assess ‘trips-not-made’, an important indirect barrier effect that is generally not included or undervalued in assessments of transport projects (Rajé, 2007).

Which indicators and which categories of destinations are most relevant for a specific assessment, needs to be determined in relation to the social groups, the research question, and the policy goals that are the focus of that assessment. This can yield a smaller or larger number of maps and results than presented here. Accessibility literature acknowledges the need for simplification if accessibility instruments are to be successfully applied to practice (Papa et al., 2015; Te Brömmelstroet and Bertolini, 2010). Despite the obvious potential for accessibility measures in spatial planning, many accessibility instruments suffer from a dilemma between rigour, i.e. the assessments are exact and complete, and relevance, i.e. the process and results are easy to understand and have meaning for planning decisions. For the general usability of direct barrier effect indicators in practice, which is an important aspect but outside the scope of this study, the indicators can be aggregated with each other into indices, or spatially, for example by using averages, to reduce the complexity of the output. This aggregation may lead to the disappearance of detail, eventually masking extreme cases, which might not be ethically acceptable. Such a complex and principal problem affects any set of indicators and is not specific to the indicator framework here developed.

6.1. Limitations

The limitations of the proposed indicators should be mentioned. A first limitation is that changes in Travel time, Choice and Catchment are measured in percentages, to make it possible to compare the results for different locations. This allows for an indication of the significance of the changes: for example, a 2-minute reduction on a 4-minute trip has more impact than a 2-minute reduction on a 20-minute trip. However, for short travel times, using percentage change can give misleading results; for example, a 100% increase on 2 min travel time is a very large increase in percentage, but only a small increase of 2 min in absolute terms. Further, describing change in percentages ignores the fact that certain benefits do not increase in a linear way. To illustrate: it is not immediately obvious that having access to eight schools is two times better than having access to four schools, and four times better than having access to two schools. It is therefore important to interpret the results as indications of the changes in conditions in the city as implied by the removal of the barriers.

A second limitation is that the indicators disregard the important role of the amenity value of mitigation measures, a subject studied by Grisolía et al. (2015), that is, the quality and comfort of the connections. In this case study, that is best noted in Frihamnen where the results for all indicators are rather low. This could be partly due to the high number of facilities planned for the area and the proposed ferry connection to the inner city, which would make connections across the motorway and railway less important. But the high accessibility results in the existing situation, without tunnels, is presumably due to the existence of a footbridge across the transport infrastructure. This footbridge is not accessible for bicycles and its comfort of use for pedestrians may be questioned. The amenity value of the connections could be dealt with in the analyses by using different networks for pedestrians and for bicycles, or by introducing a system of penalties in the model related to their quality, comfort or safety.

It should be mentioned that the tunnel scenario was chosen for this study as it is the clearest in terms of showing the effects of the barriers. However, there are other, less expensive alternatives to reduce barrier effects, such as constructing bridges that enable cross connections. The extent to which these measures can mitigate barrier effects can then also be assessed with the proposed indicators.

6.2. Next steps

As the case study focused on demonstrating the potential of the indicators, the parameters used in the analyses were based on general assumptions about the wishes, needs, and capabilities of the general population of the area, rather than those of specific social groups. This aspect needs to be further developed because barriers affect individuals in different ways, as several authors point out (Clark et al., 1991; Mindell et al., 2011; Nimegeer et al., 2018). Further research is still needed regarding adapting the indicators to specific social groups, and to explicitly address their needs, wishes and capabilities. The focus should be on adapting the parameters of the proposed indicators to analyse the effects of barriers, taking into account the different conditions such as destinations, travel times, and modes, pertinent to different social groups. At the same time, it is important to take into account possible future demographic changes, since the aim is to have a method for decision support of transport infrastructure interventions to be executed in ten or twenty years' time, when the composition of the population may have changed considerably.

Based on Papa's classification (Papa et al., 2015), the proposed set of local accessibility indicators for direct barrier effects can be defined as a multiple planning orientated instrument, relating to both transport and land use, and a passive decision support (PDS), in the sense that it "aids the process of decision making but cannot identify explicit decisions, suggestions, or solutions (Papa et al., 2015, p.62). For the application of this instrument in practice, it will be important to test the indicators in real-life projects to determine the advantages and drawbacks of the metrics, and in which phase of the evaluation and process of developing alternatives they are of most use. In dialogue with practitioners, it can then be determined how best these analyses of direct barrier effects can contribute quantitative support for assessments related to indirect and wider barrier effects, such as child impact assessments and traffic assessments.

Another essential step towards a method for the assessment of barrier effects, which is the final goal of the research project, is the formulation of principles for the valuation of barrier effects. One option for this valuation is monetization; Anciães and Jones (2020) have developed new tools for the monetization of the barrier effects of dynamic barriers based on stated preference and revealed preference techniques). Another possible option for valuation is to measure the extent to which an investment in transportation infrastructure increases or reduces conditions for reaching given political goals.

7. Conclusions

The purpose of this paper was to introduce direct barrier effects of transportation infrastructure as a theoretical and practical case within the research field of accessibility, and to demonstrate how these barrier effects can be quantified with simple local accessibility indicators, which addresses a current need from practice. The literature on barrier effects points to the need for taking the transport system, people's abilities and needs, and the land use system into consideration, three aspects that are conceptually aligned with the components of accessibility. From the literature, barrier effects are categorised into direct, indirect and wider effects, where direct effects are detours and time loss. Based on the direct barrier effects identified in the literature, four local accessibility indicators were proposed: Travel time, Choice, Catchment and Service efficiency. As the research project is focused on applicability to the assessment of transport infrastructure projects, the indicators are based on relatively simple measures that should be easy to implement and understand. In the case study, the indicators have demonstrated their potential to quantify direct barrier effects and to capture the spatial distribution of these effects. As a result, the indicators can give valuable input for assessments of indirect and wider barrier effects. For example, the indicator Choice allows for the estimation of trips-not-made, which can provide quantitative support for social impact assessments of transportation investments.

The existing accessibility literature explains how the present-day focus on optimising mobility can lead to low density sprawl which can reduce accessibility. This study complements this literature by demonstrating how the focus on mobility can even lead to a reduction of accessibility in situations where there is a relatively high density of buildings and a geographically close proximity to destinations. Further, it shows how the concept of accessibility can provide a suitable theoretical framework to the existing theories of barrier effects, and how these effects can be quantified with simple accessibility indicators.

The proposed indicators represent the beginning of the development of a quantification method for assessing direct barrier effects of transport infrastructure projects that can give objective information about the effects of barriers, allowing for better informed decision-making processes concerning investments in infrastructure. In consequence, measures to reduce barrier effects could be prioritised. Such reductions in barrier effects can have far-reaching societal impacts, from an increase in accessibility to destinations and a reduction in social segregation, to an increase in the potential for active travel such as walking and cycling, thereby improving health. Furthermore, a quantification method can improve equity and efficiency in negotiations about infrastructure projects, by providing local stakeholders such as municipalities and local communities with objective data to underpin their arguments.

CRediT authorship contribution statement

Job van Eldijk: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization, Project administration, Funding acquisition. **Jorge Gil:** Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing, Supervision, Project administration. **Natalia Kuska:** Formal analysis, Investigation, Data curation, Visualization. **Rashmita Sisinty Patro:** Formal analysis, Visualization.

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Declaration of Competing Interest

None.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trd.2020.102410.

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