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The Problem of Accessibility in Sustainable Mobility

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Introduction

The evaluation of accessibility is a serious and unsolved issue in sustainable mobility. Currently, countless different methodologies and approaches have been developed to measure and evaluate this multifaceted concept.

This paper is divided into two main sections. The aim of the first part is to provide an overview on the existing literature about the topic of accessibility in sustainable mobility (Chapter 1). The main extent of the literature review is to capture and explain the great heterogeneity that thoroughly permeates the accessibility concept, providing many examples coming from the theories analysed (Chapter 2). Moreover, the Accessibility Paradigm developed by Geurs and Van Wee will be analysed and discussed, in order to highlight the strengths and weaknesses of the holistic indicators (Chapter 3).

The literature review has been realised through a research on Google Scholar, using as keywords 'accessibility', 'sustainable mobility', 'accessibility paradigm', 'accessibility measures', 'accessibility and perceived opportunities', 'perceived accessibility'. The resulting articles where analysed, summarised and selected basing on their relevance and number of quotes.

In view of the foregoing, the second part is aimed at the proposal and test of an indicator of accessibility (Chapter 4). The study does not have the claim to find a new absolute standard measure. However, it is an experiment to demonstrate that is possible to derivate an intermediate indicator between simplified mobility theories and holistic models that present an unambiguous behaviour when changing the values of the parameters. The empirical application of the indicator is developed through the comparison of the accessibility levels of selected attractors in two different scenarios. The first scenario will analyse and compare the accessibility levels of two different attractors in the city of London, while in the second scenario two similar attractors located respectively in London and in Berlin will be compared. Both the case studies were developed in a GIS environment.

The data employed in the London case were gathered on London's Department for Transport official website, "London Datacentre" website, the official London's public transport website "Transport for London" and on "Citymapper" website. On the other side, Berlin's data were gathered on the German "Federal Highway Research Institute" website, the German Statistics Federal Bureau website and the Berlin's official online website. All the information about population composition come from "City Population" website. All the data used in the empirical application refer to the current situation in 2017.

After an evaluation of the result obtained, a more generalised weighted indicator will be proposed and discussed. Strengths and weaknesses of the proposed indicator will be explained and highlighted in order to give a broader view on the possible applications of a similar accessibility indicator.

The conclusions deriving from this experiment will be presented and discussed, providing suggestions for further researches.

Chapter 1

STATE OF THE ART

In the last decades, accessibility has been one of the most important concepts in the fields of transport policy and research, economic development and urban planning. Accessibility expresses the extent to which individuals can have access to a set of activities using different transport modes. In other words, it may be used to define what can be reached and how from people in a given point in space and time. Therefore, the increase in accessibility is one of the key concepts when making new urban mobility plans and transformations in land use.

According to the literature, the concept of accessibility experienced a deep and continuous evolution. In 1959 Hansen published "*How Accessibility Shapes Land Use*", where he defined accessibility as "the potential of opportunities for interaction" departing from the usual definition of accessibility as a mere measure of the ease of interaction. In particular, Hansen explained that "accessibility is a measurement of the spatial distribution of activities about a point, adjusted for the ability and the desire of people or firms to overcome spatial separation" (Hansen, 1959). This is still one of the most known and shared definition of accessibility.

In the past, the main aim of urban planning was to improve the efficiency and increase the capacity of the road network. The focus was on the road traffic and its relative measures, as average speed, volume-to-capacity ratio, and service level of the road network. Starting from the 70s the concept of road traffic was overcome in favour of the more comprehensive concept of "mobility". It was the turning point from the simple statistics representing the road traffic to a multimodal approach. It was no more a matter of improving roads efficiency and capacity, but of transfer of persons using different transport modes. Now many different alternatives to the car travels were considered, including travel using public transports as bus or train, cycling and walking (Papa, 2018).

In 1973 Wachs and Kumagai published "*Physical Accessibility as a Social Indicator*" and employed accessibility as the measure of "the average number of opportunities which the residents of the area possess to take part in a particular activity or set of activities". While they focused on the importance of the number of opportunities to be reached by people, Leonardi wanted to go a step further, moving the attention to the individual needs and net utility achievable by individuals. People usually travel to reach a destination where to perform an activity, and the value that they give to that activity results in a specific travel. Then, travel is a derived demand and not an activity undertaken for its own sake (Banister, 2008). Following this concept in 1978 Leonardi highlighted the relevance of the net utility that persons can achieve undertaking a travel, explaining accessibility as "the consumer surplus, or net benefit, that people achieve from using the transport and land-use system" (Leonardi, 1978).

As we can see from Table 1, many other definitions followed. Bertolini generalized the concept, trying to include in the definition of accessibility both the mobility part and the consumer surplus part. He adopted a multimodal approach using accessibility to evaluate both *what* individuals could reach from a given point and *how* they could reach their destination. Finally, Geurs and Van Wee gave the most comprehensive and complete definition so far, underlining how accessibility expresses the relationship that coexists between the transport system and the system of activities or destinations desired by individuals. This kind of approach is the most suitable one until now, since it tries to develop and relate many variables affecting accessibility. Recently many researchers have shared and re-proposed the so-called paradigm of accessibility developed by Geurs and Van Wee.

1959	Hansen	*"accessibility is a measurement of the spatial distribution of activities about a point, adjusted for the ability and the desire of people or firms to overcome spatial separation"*
1973	Wachs and Kumagai	*"the average number of opportunities which the residents of the area possess to take part in a particular activity or set of activities"*
1978	Leonardi	*"the consumer surplus, or net benefit, that people achieve from using the transport and land-use system"*
2004	Geurs and Van Wee	*"the extent to which land-use and transport systems enable (groups of) individuals to reach activities or destinations using a (combination of) transport mode(s)"*
2005	Bertolini	*"what and how can be reached from a given point in space"*
2013	Cascetta	*"a concept expressing the relationship between the activity system in a territorial area and the transportation system serving it"*

Table 1 - Definitions of accessibility

As we have seen, accessibility is related to the need of individuals or groups of individuals to meet their needs by carrying out a specific activity or a set of activities. With a first analysis of the literature it is possible to divide active from passive accessibility. Active, or origin accessibility reflects the easiness for a subject to reach a certain place where to carry out the activities to satisfy his needs. On the other hand, passive, or destination accessibility represents the easiness for an activity located in a certain area of being reached by the potential users (Papa, 2018).

The role of accessibility was highly debated in literature by many researchers. In Table 1 we summarised only a few of the many definitions that can be found when studying this complex topic. The main problem is that there is a lack of a basic common knowledge on which all the researchers can agree. This great heterogeneity in the concept is reflected by the huge amount of different accessibility measures that have been used.

1.1 Different Approaches to Accessibility

Depending on the nature of the measures used, we can distinguish between quantified and non-quantified approaches. We define as quantified approach (also called objective approaches) the model which employs shared and objective unity measures, commonly accepted by the scientific community, e.g. kilometres per hour, metres, hours, density measures, etc. On the other side, a non-quantified approach (or subjective approach) is a model which uses alternative units of measurement rather than the standards one, e.g. levels of comfort, level of satisfaction, Likert-type scale measurements, etc. Of course, the more the phenomenon that has to be measure is simplified, the more it will be quantifiable.

1.1.1 Quantified Approaches

Quantified approaches were mainly used in the past, when the focus was on mobility and land use measures. Accessibility, then, was mostly expressed through transport speed, access and travel costs, network efficiency, volume-to-capacity ratio, and road traffic, considering a given time interval. Since the transport planners had to consider the distribution of the activities on the territory, the empirical examinations about people in a given area were also important. They observed the number of residents, work opportunities, and the number of sanitary and leisure facilities.

Three main issues arise from this kind of approach. First, the mobility paradigm undervalues the interrelations between transport system and land use. Second, it does not pay attention to the degree of transport system's social impacts. Third, it does not correctly assess the geographical distribution of the impacts of new infrastructures or transport services (Papa, 2018).

The accessibility paradigm developed by Geurs and Van Wee (2004) is oriented towards holism and permits to overcome these limitations, by identifying and relating 4 fundamental accessibility characteristics that we will describe more in-depth later: land use, transport, temporal and individual components. Even though this model overcomes many difficulties focusing on the relationships that coexist between the components trying to capture the dynamism of the environment in which we operate, it is still based on quantitative data and statistical measures. This approach still completely ignores the relevance of consumer's perceptions that can be expressed by qualitative data. Quantitative data are not able to explore the multifaceted users' perceptions of accessibility depending on their own opportunities – hence, the importance of non-quantified approaches to accessibility.

1.1.2 Non-quantified Approaches

Non-quantified approaches to accessibility might describe more characteristics about the relationship between individuals and accessibility, for instance considering an individual's perception of an activity, a set of activities or an area to be accessible. Thanks to the accessibility paradigm we include the number of shops, cinemas, schools, and all the leisure and social facilities in the land use component, actually introducing the consumer's needs in the model. However, the user's perceived accessibility is still missing. Perceived accessibility is defined as "how easy it is to live a satisfactory life with the help of the transport system" (Lättman, Friman, & Olsson, 2018). In other words, the authors link the accessibility while using the transport system to both the ease of getting the transport system and to the individual's ability to live the life he or her wants helped by the transport system. This is in line with the explicit goal of the European Commission stating that transport policies across Europe must be "for all", satisfying each individual needs and perceptions (European Commission, 2015). Furthermore, the Social Exclusion Unit (SEU) points out how individual perception of context and opportunities may affect perceived accessibility, since some characteristics as feelings of safety and security or available information of transport options are involved in the cognitive processes of the users (Lättman, Friman, & Olsson, 2018).

The next chapter will focus on the different definitions of accessibility presented above, trying to give an explanation to a such great heterogeneity.

Chapter 2

Heterogeneity in the Concept: Why?

Accessibility is a concept that experienced a continuous evolution, and many different definitions were provided during the years. However, there are many different definitions dating back not only to different time intervals but to the same period of time. The heterogeneity confirmed by the literature we examined is widespread and seems to be unsolvable, due to the lack of a common and shared base on the topic. At this point it is interesting to investigate which is the cause of a such great heterogeneity.

Referring to the literature we presented in the Chapter 1, we can see that each definition of accessibility used by the authors is the result of the scenario they wanted to examine. In other words, depending on the environment the authors intended to explore and the measures they were willing to use, they proposed a slightly different definition, able to match their researches. It does not exist a unique definition of accessibility since a shared common knowledge on the topic is missing. Accessibility is a problem with multiple dimensions and involves many fields of research. Then, the authors create an ad-hoc definition able to better explain and answer to the problem they are handling in relation to the dimension of accessibility they are considering. Providing a holistic view of accessibility may be extremely complex, both because of the complexity of some measures and because some of the components have a conflicting behaviour. Looking at accessibility from different perspectives separately is simpler and highlights the problem at handle, giving more specific results. Therefore, heterogeneity is due to the different perspectives and objectives of the various researches. In particular, depending on the accessibility measures employed we can distinguish three macro areas of study: statistic, economic and social field.

1. The statistic field includes all the researches in transport mobility, urban and geographical studies which use quantitative data such as transport speed, network efficiency, volume-to-capacity ratio, road traffic and gravity-based measures. These measures are widely recognised and used by many authors and urban planners. Hansen (1959), Vickerman (1974) as well as Bertolini (2003), Geurs and Van Wee (2004) apply this kind of data.

   For instance, Hansen (1959) used his Accessibility Model to prove how accessibility and land use are related. He calculated accessibility in 70 areas of Washington by using the well-known gravity model and he mapped the results on a topographic map. Then, he estimated the residential growth in each area with "accessibility to employment" and "vacant land" as independent variables and compared it with actual growths. The results he obtained were promising and quite accurate. However, gravity models ignore the taste variation, that is the variation of an attribute across individuals.

   Moreover, Bertolini, Le Clercq and Kapoen (2005) related the concept of accessibility to economic, environmental and social goals and show how sustainable mobility may be used to integrate transport and land use in an interactive plan-making process. The study interested two areas of the Netherlands, Rotterdam-The Hague area and Delta Metropolis. To compute accessibility, they used cumulative opportunity measures expressed in terms of spatial opportunities reachable within a given time of travel (30 minutes). In particular, they started drawing isochrones from the main urban nodes and calculating the number of jobs and inhabitants within isochrone. Finally, they analysed the effects of changes in transport provision and land use growth. The results they obtained are interesting because they show the inter-relation between the variables. However, the isochrones approach is simpler than the gravity model and it still does not take into account competition.

2. The economic field consider all those studies focused on utility, consumer's surplus and net benefit deriving from accessibility, using formulas derived from the economic theory. Many researchers studied how accessibility influences economic growth and how it is related to the consumer surplus. Two basic approaches are possible:
    - the micro-economic methods are used to examine the direct economic impacts in cost-benefit analysis through the classical welfare theory. The most used measures are the Marshallian consumer surplus, that is the consumer's willingness to pay beyond the current market price, and the Hicksian compensation variation, or the income transfer required to maintain the same utility level (Geurs and Van Wee, 2004). This is the approach used by Leonardi (1978) in his "Optimum Facility Location by Accessibility Maximizing", where accessibility is represented by the net utility received by a subject in a given location who achieves his or her destination through the transport system.

- the macro-economic methods are used to study the wider economic impacts, usually using the production function approach with GDP as a measure of economic benefit (Geurs and Van Wee, 2004). Banister and Berechman first in 2000 and then in 2001, studied the link between investment in transport infrastructure and economic development. They found that an increase in investments in infrastructure stocks is reflected by an increase in accessibility, which might potentially increase the economic activity through employment and factor productivity. Banister and Berechman (2001) highlighted that this happens only in case of major changes in the accessibility system as a whole, and competition effects must be well evaluated.

3. The social field consider the inquiries on the individuals and groups of individuals and how they are related to accessibility and the consequences deriving from a lack of accessibility (i.e. social exclusion). In this field, accessibility measures can be used as social indicators if they can show availability for social and economic opportunities for the individuals, such as availability for employment, health services or social interaction. Moreover, analysis on social equity impacts are included, as well as the influence of political or institutional factors and the consequences they have on the perceived accessibility. Wachs and Kumagai (1973), Cascetta, Cartenì and Montanino (2013) and Lättman, Olsson and Friman (2018) consider this kind of topics from many different perspectives.

   One of the most important and well-known contribution is the one by Wachs and Kumagai, who used accessibility as a measure of "social report" to study the current situation in 1973 in Los Angeles. They proved that significant differences exist between accessibility to employment and accessibility to health care opportunities. Moreover, they demonstrated through the analysis that those differences were related to the communities' socio-economic status and to their spatial location within the region. Therefore, they concluded that accessibility indicators must be included in transportation policy-making in order to provide equal opportunities (Wachs and Kumagai, 1973).

Cascetta, Cartenì and Montanino, instead, studied another aspect of the social field, proposing a new indicator based on perceived opportunities. In other words, they presented a model based on the user's perception of accessibility and compared their results to the ones of gravity-based and isochrones-based models relative to the district of Naples. The results showed how cognitive processes of the individuals influence their definition of accessibility, providing to each a different perception of space and location. Furthermore, the authors underlined how is internet-based comparative searching and best-price alternative research affect individual's perception (Cascetta, Cartenì and Montanino, 2013).

Finally, Lättman, Olsson and Friman, treated exactly the problem of perceived accessibility, highlighting how different opportunities, such as a different health status or income, affect the consumer's perception of accessibility. In this case, they developed the Perceived Accessibility Scale (PAC) to examine the level of perceived accessibility of individuals and they compared the results to the ones obtained with standard accessibility measures. They concluded that measures of perceived accessibility must be included in transport system evaluation and planning (Lättman, Olsson and Friman, 2018).

Although in recent years most surveys and researches try to explain and explore accessibility as the result of these three macro areas interconnected, they still fail in this objective, mainly due to the conflicting nature of the trade-offs between the components. Finding a holistic indicator for accessibility is an extremely difficult task, since holistic approaches tend to be either too generalized and approximated or inapplicable and unrealistic.

From this fuzzy background, the accessibility paradigm suggested by Geurs and Van Wee (2004) emerges as one of the more important models up to now. This model identifies four components of accessibility and link them to different accessibility measures, trying to look at the context from different perspectives. In this sense, the accessibility paradigm is oriented towards holism, since it tries to capture the great variety of the environment. In particular, it covers completely what we defined the statistical and the economic field, and includes a great part of the social field.

Chapter 3 will describe in-depth Geurs and Van Wee's accessibility paradigm model, in order to give a complete overview both on the theoretical and computational part, underlining its advantages and disadvantages.

Chapter 3

THE ACCESSIBILITY PARADIGM

The Accessibility Paradigm is a model developed by Geurs and Van Wee in 2004, published in the article titled "*Accessibility evaluation of land-use and transport strategies: review and research directions*". It represents a comprehensive summary of the past theories, since the authors managed to combine almost completely the statistic, economic and social fields presented in Chapter 2, providing a standard that might be successfully used in transport and urban planning. Geurs and Van Wee, by classifying four different components that influence accessibility, created a holism-oriented model, able to overcome the main limitations presented by the models of the past. In particular, it emphasizes the relationship between the transport system and land use, paying attention to the social impacts of the transport system, and evaluating the geographical distribution of the impacts of new infrastructures or transport services.

3.1 Description of the Model

As previously announced, Geurs and Van Wee detected four accessibility components and defined them as follows:

1. The *land-use component* describes the land-use system. It indicates the quantity and quality of opportunities supplied and their spatial distribution in a given location. Moreover, it describes the opportunities' demand, comparing it to their respectively supply and studying their relationship. This component includes the number of shops, workplaces and inhabitants, and health, leisure and social facilities.
2. The *transport component* represents the transport system. It is described by the disutility for each individual to reach a chosen location using a specific transport mode. It is defined by comparing the supply of infrastructures, including their locations and characteristics, to the demand of passengers and freight travel. This component includes travel, waiting and parking time and costs, and different efforts, as reliability, comfort level and accident risk.
3. The *temporal component* outlines the time constraints. It reflects the number and distribution of activities during the day, and the time that an individual can spend to participate in or take advantage of those activities.
4. The *individual component* shows the needs, abilities, and opportunities of individuals in terms of age, gender, income, health status, level of education, household situation, availability of travel modes, travel budget, etc. All these characteristics are important because they may limit people's access to travel modes or give to individuals the perception of being excluded from access to such travel modes.

Following this definition of accessibility, Geurs and Van Wee identified four different set of measures such that all the four components of accessibility were taken into account from different perspectives.

1. *Infrastructure-based* measures are typically used in transport planning. They investigate the performance of a transport system, analysing data that are usually readily available such as the level of congestion, time lost in congestion and average speed. However, infrastructure-based measures ignore transport strategies' potential impacts of land-use and do not correctly assess land-use strategies' accessibility impacts, affecting the spatial distribution of activities.
2. *Location-based* measures are usually adopted in urban planning and geographical researches. They analyse the accessibility at a position on a macro level, including capacity constraints of supplied activities and competition effects. Data refer to the spatial distribution of activities considering a time gap, such as 'number of shops within 20 minutes travel from the origin'. It is possible to distinguish between: distance and contour measure, potential measure, adapted potential measure and balancing factors.
    - Distance (or connectivity) measure is the simplest way to evaluate the degree at which two places or points are connected, usually representing the maximum travel time or distance by a straight line. To consider more than two destinations, a contour (or isochronic) measure is employed. This method "counts the number of opportunities that can be reached in a given time, travel distance or cost (fixed cost)", or calculate the time and cost required to have access to a given number of opportunities. This measure is also called cumulative opportunities, proximity count or daily accessibility (Geurs and van Wee, 2004). However, it does not

measure the effects of land-use combined with the transport component, it does not consider competition effects and it does not take into account perceptions and preferences of individuals.

- Potential (or gravity-based) measure assesses “the accessibility of opportunities in zone i to all other zones (n) in which smaller and/or more distant opportunities provide diminishing influences” (Geurs and van Wee, 2004). This measure overcomes some limitation of the contour measure, since it estimates the effects of land-use and transport combined, and individual’s perceptions are included by using a distance decay function. The formula, which assumes a negative exponential cost function, is as follows:

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

where

A_i is the accessibility in zone i to all opportunities D in zone j, β is the cost sensitivity parameter and c_{ij} is the travel cost between i and j.

Nevertheless, this measure is difficult to be interpreted and communicated and it does not consider competition effects.

- Adapted potential measure is used to incorporate competition effects into the potential measure. Some authors divide the number of reachable opportunities within region i (i.e. the supplied potential in the origin zone) by the potential demand from zone i, including the effect of competition on opportunities. Others make the quotient of the reachable opportunities within region i (i.e. potential supply) to the number of opportunities from each destination j (i.e. potential demand).

- Balancing factors approach includes both competition on supplied opportunities and competition on demand. The balancing factors, named a_i and b_j, are mutually dependent and "ensure that the magnitude of flow (e.g. trips) originating at zone i and destined at zone j equals the number of activities in zone i (e.g. workers) and j (e.g. jobs)". Assuming the negative exponential demand function, the balancing factors form is the following:

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

$$b_j = \sum_{i=1}^{n} \frac{1}{a_i} O_i e^{-\beta c_{ij}} \tag{3}$$

where

a_i is the balancing factor in zone i of the ratio of opportunities D in zone j to b_j, β is the cost sensitivity parameter and c_{ij} is the travel cost between i and j

and

b_j is the balancing factor in zone j of the ratio of opportunities O in zone i to a_i, β is the cost sensitivity parameter and c_{ij} is the travel cost between i and j.

Since the formula includes both the demand and supply locations weighted by a distance decay function, it is difficult to be interpreted and communicated.

3. *Person-based* measures refer to constraints of an individual's freedom of action in a specific environment. They examine accessibility at individual level, considering data such as the "number of activities a person can undertake at a specific time". Particular importance is given to space-time prisms derived from the space-time geography (Hägerstrand, 1970), that are able to describe travelling patterns including constraints in space and

time. The result is the recognition of the opportunities' potential areas reachable in a given time. However, person-based measures are not suitable to evaluate competition effects, require large amount of data and therefore are usually applicable only to restricted areas or small population.

4. *Utility-based* measures derive from economic studies. They evaluate the net economic benefits that individuals may achieve by getting access to activities located in a certain area. In general, these measures are difficult to be interpreted but presents many advantages in economic evaluations. This kind of measures show diminishing returns and may give as result to improve accessibility in locations with low levels of accessibility rather than in locations readily well accessible. This will have important implications in evaluating social and economic situations regarding land-use and transport plans. The authors identify the following three approaches in literature:
   - The logsum benefit measure weighs the attractiveness of a complete set of choices. It derives from random utility theory and uses the logsum (i.e. the denominator of the multinomial logit model) as an accessibility measure. The formula has the following form:

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

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

     where

     A_i is the maximum expected utility and v_{ij} represents the utility's observed transportation, temporal and spatial components. Nevertheless, with this method it is not possible to compare different model specifications. In order to do so, you can convert accessibility into monetary terms calculating the consumer surplus by dividing equation (4) by a travel-cost coefficient. Moreover, the logsum benefit measure can be linked to compensation variation by dividing equation (4) by a marginal utility of income (i.e. $\delta v_{ij}/\delta y_i$where y_i denotes the individual's income). However, the utility function must be linear with respect to income to obtain unambiguous results in monetary terms.

- The balancing factor benefit is a measure derived by the integral transport-user benefit measure by Williams (1976). The form of the formula states as follows:

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

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

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

where

A_i denotes the expected benefits per trip generated, A_j the expected benefits per trip attracted and A_{ij} the expected benefits per trip for between region i and j, for a predefined transport situation and complying with the entropy model's total trip origin and destinations.

The main advantage of this model compared to the logsum benefit one is that includes the effects of competition. However, even with this model is required a linear utility function with respect to income to interprets results in monetary terms unambiguously.

- The space-time approach has been combined with the utility-based approach to get a measure which includes temporal constraints. The result is a space-time utility accessibility measure (Miller, 1999) where the time available to participate in an activity is a variable of the logsum measure utility function. Nonetheless, as well as the other utility-measures, it presents problems regarding the availability and the complexity of the data required, and is difficult to be interpreted and communicated.

Geurs and Van Wee evaluated the usefulness of the accessibility concept in assessing land-use and transport changes, dividing the different accessibility measures they employed according to four different criteria: “theoretical basis”, “operationalisation”, “interpretability and communicability”, “usability in social and economic evaluations”.

The *theoretical basis* criterion reflects the ideal requirement for each measure to take into account all the four accessibility components. Therefore, Geurs and van Wee state that an accessibility measure should be sensitive to transport system and land-use system changes, opportunities’ temporal constraints and should consider needs, abilities and opportunities of the individuals. Particular importance is given to competition effects, since a lack in correctly estimating competition may lead to deceptive results.

Operationalisation means how easily the measures are usable in practice. This criterion is usually conflicting with at least one or more theoretical criteria. *Interpretability and communicability* criterion indicates the ability and ease to understand and communicate the measures. Indeed, if planners or researcher are not able to correctly interpret measures, they are useless.

Finally, *usability in social and economic evaluations* refers to the fact that accessibility measures may be used as social and economic indicators. More specifically, accessibility measures are employed as social indicators if “they show the availability of social and economic opportunities for individuals”. This field may cover the evaluation of social equity impacts, too. On the other side, measures of accessibility are used as economic indicators when they evaluate direct or indirect economic impacts. It is possible to use both micro- and macro-economic theories depending on the impacts you want to evaluate. Finally, the economic benefit may usually be represented through an accessibility measure, if it acts as an input to calculate land use or transport changes' economic benefits.

Section 3.2 will weigh the advantages and disadvantages of the model, trying to correctly evaluate the suitability of the accessibility paradigm.

3.2 Strengths and Weaknesses of the Model

Geurs and Van Wee's Accessibility approach is a smart summary of the past literature and research, which enhances to overcome some constraints of the theories of mobility used to examine transport and land-use changes and improvements.

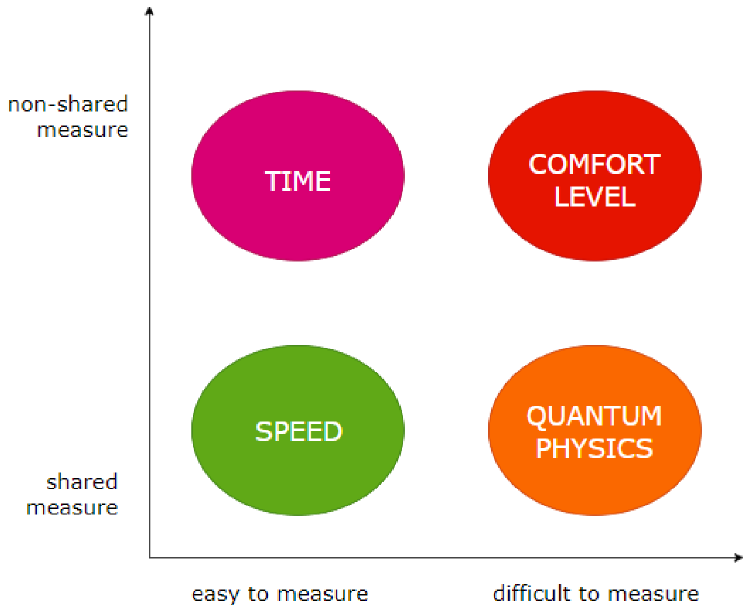
Mobility theories exploit a thorough scientific method to investigate the environment taken into account. Nevertheless, during transport and land-use plan-making and research, a complex system of many variables is considered, that is extremely dynamic and may results in changes in transport and policy system as well as economic and social situation. Due to the analytical nature of mobility studies, they tend to underestimate the relationships existing between transport system and land-use and their combined effects in the environment. Moreover, they do not achieve a satisfying degree in evaluating the social impacts of the transport system and do not assess the geographical distribution of the impacts of the introduction of new infrastructures or transport services. All these aspects are considered by the accessibility approach.

According to Papa, the accessibility approach by Geurs and Van Wee presents many advantages (Papa, 2018):

1. it is a holistic model and recognises that many different components affect accessibility. The accessibility approach studies analytically each component to examine the whole system;
2. it focuses on the multiple interactions existing between its components, producing results based on their combination and studying the relationships existing between them;
3. it understands that the lack or collapse of a component of the model is sufficient to prevent people to access to what they might need or desire;
4. it acknowledges, therefore, that increasing investments to improve one of the accessibility components may not enhance the overall accessibility of a location, activity or a set of activities.

Theoretically, the accessibility paradigm seems to be the best and more comprehensive way to evaluate accessibility. Nevertheless, applying this model may present some problems.

Generally speaking, let's start dividing scientific procedures between "easy to measure" and "difficult to measure" depending on the easiness of the method required to calculate the result. For instance, 'capacity' or 'speed' are extremely easy to measure, while 'comfort' or 'econometric models' are difficult to measure, since each of us has a different perception of comfort levels and econometric models require complex formulas. Then, we distinguish between "shared" and "non-shared" measures. Shared measure comprehends all the procedures commonly agreed by the scientific community, such as the 'weight' or 'quantum physics models'. On the other side, non-shared measure indicates all those measure on which the scientific community do not agreed, such as 'time' or 'satisfaction'. In Graph 1 is shown how these four elements may be combined creating a simple matrix.



Graph 1 – Examples of different measures.

The study of accessibility might follow the same pattern: some models are easy to measure and use shared measurements but are too simplified; others use non-shared methodologies and are extremely difficult to measure. On the other hand, some models are easy to quantify but are less accepted because they use non-shared measures; others use shared measures but are more difficult to calculate. Since, as said before, accessibility is a concept with many components, the model used always depends on which accessibility dimension the researches intend to investigate.

In the development of a holistic model, it is necessary to consider the problem from all its perspectives, taking into account the multitude of relationships within its components. However, if the considered components rely on different side of the matrix in Graph 1, it is clear that it will be extremely difficult to evaluate unambiguously the results of a similar indicator.

Geurs and Van Wee proposed an extremely complete indicator, yet actually inapplicable. Evaluating the trade-offs between the components they identify, is a task that can not be achieved unambiguously, since the elements are usually conflicting in one or more of their parts.

For instance, let's consider a great investment in the transport system, that increases the mobility component and reduces travel time. This increase in mobility will affect the land-use component, maybe causing the activities to move from the city centre to rural areas, now more easily achievable. Nevertheless, due to the improvements the travel costs may increase causing a decrease in the individual components, given the same people's wealth status. This will not only affect the temporal component but will lead to a problem of social exclusion too.

Even a simple situation like the one proposed above, clarifies how there is no a unique way of interpreting a variation in accessibility, since an increase in the total value does not imply a growth in all of its components and the trade-offs between them are difficult to be weighted.

In the next chapter we will try to develop a new accessibility indicator, taking into account the past literature and trying to overcome the limitations found in the accessibility approach.

Chapter 4

MEASURING ACCESSIBILITY: AN EMPIRICAL TEST

The second part of this paper is focused on a proposal for an indicator of accessibility.

The indicator here presented aims at including the main accessibility components while being simple enough to be adopted in urban transport planning and assessment. The goal is to develop an intermediate solution between trivial mobility models and holistic models.

We decided to develop an indicator of accessibility focused on the existing infrastructures in a selected location, rather than according to subjective features, such as satisfaction or comfort derived from the use of the transport system.

Referring to Graph 1 in paragraph 3.2 the proposed indicator will use shared measures and a medium level of complexity in measurement. Moreover, the index will cover three out of the four accessibility components identified by Geurs and Van Wee reported in paragraph 3.1. In particular, we will focus on the land-use, transport and temporal components.

4.1 The Accessibility Index

We started focusing on which relevant accessibility characteristics should be considered first in developing the indicator, and how they affect accessibility.

Foremost, we consider that each component, as well as accessibility itself, depends on two important variables:

- the time of the day or, more generally the day of the week, or even the week of the year, etc. in which we make the measurements (t);
- the geographical area in which the origin and the destination lie (s).

The first component that has been adopted is the Traffic Volume Count (TVC) to calculate the traffic over a road. This measure can be used to compute both vehicular or pedestrian traffic and it is defined as the number of vehicles or persons passing through a road in a period of time. An increase in TVC means a decrease in accessibility, since a great traffic towards a location, may prevent some people to have access to their destination or, in general, decrease the total number of people that will reach it. This is true if we are considering an activity or a set of activities, too. TVC may vary depending on the time in which the analysis is conducted (e.g. traffic may be different at 8:00 a.m. on Monday morning or at 11:00 p.m. on Sunday night) and depending on the area considered (e.g. traffic may change near a train station or near a small grocery).

The second component that has been included is the congestion component in order to measure the road performance in different situations. In the formula, the congestion level has been represented by the Volume-to-Capacity Ratio (V/C). Of course, a higher V/C Ratio results in a decrease in the total accessibility level, since it will be more difficult to have access to a destination due to a longer travel and waiting time. V/C Ratio may change depending on the time in which the data are gathered (e.g. congestion may variate in peak hours rather than in off-peak hours) and depending on the zone considered (e.g. congestion may be higher in the city centre than in rural areas).

The third component that has been considered is related to the travel time, in particular it is the average travel time (T_{ij}) that a person employs to go from the point of origin to his or her destination. Accessibility and average travel time are indirectly proportional since an increase in one of them implies a decrease in the other. The average travel time may fluctuate depending on when we decide to run the analysis (e.g. the average travel time may increase if it is a time of the day in which congestion is high, or decrease otherwise) and depending on the geographical area considered (e.g. variations due to roadworks, assuming the same travel length).

Meanwhile, the travel length (L_{ij}) affects accessibility, too. L_{ij} represents the length of the journey to go from the point of origin to the desired destination. Looking at the overall accessibility, a decrease in travel length should be reflected by an increase in the total level of accessibility, since a nearest destination seems to be more accessible. The travel length may vary depending on the time in which the data has been gathered (e.g. when it is necessary to take an alternate road to reach the destination due to a night road block) and depending on the desired path (e.g. variations from the standard path due to deviations, such as one-way or closed roads).

The average speed of travel (AV_{ij}) is another important component of accessibility. Indeed, considering car journeys, if the point of origin and the destination are connected by a highway, the location, activity or set of activities that could be evaluated will seem highly accessible, thanks to an easy and fast way to reach them. On the other hand, if the destination is in the countryside and reachable only through county roads where the average speed is slower than in highways, it will be perceived as far less accessible. The average travel speed may depend on the time considered for the analysis (e.g. average speed may fluctuate from the daytime to the night-time) and on the analysed zone (e.g. there might be differences in average speed in the mountains or on the plains).

Then, it is important to consider accessibility costs, since the cost of travel affects the accessibility of the considered location, activity or set of activities. In particular, the cost function used in the formula is assumed to be a negative exponential function, since it should better represent the travel behaviour theory. In this index we have introduced the cost of transport as an element which reduces the overall value of accessibility.

In order to define a more detailed cost function, it has been assumed that the role of cost is affected by an elasticity parameter β that produces a marginal decreasing impact on accessibility itself. For this reason, the cost has been expressed as $e^{-\beta c_{ij}}$. The parameter β indicates the cost sensitivity, therefore the income that the persons are willing to spend to purchase travel tickets or to pay tolls during their journey. In other words, it specifies to which extent the demand will fluctuate given a variation in travel costs. In a selected area such parameter can be considered constant (i.e. it is estimated upon population rather than on individuals). Of course, this is a significant limitation of the index with respect to the actual possibility to fine-tune the Accessibility Index on different social groups. On the other hand, this limitation is typically accepted in literature. Even the costs may fluctuate depending on the analysed time (e.g. both in the long and in the short run there are many price variations) and on the considered area (e.g. costs are differentiated from a selected area to another).

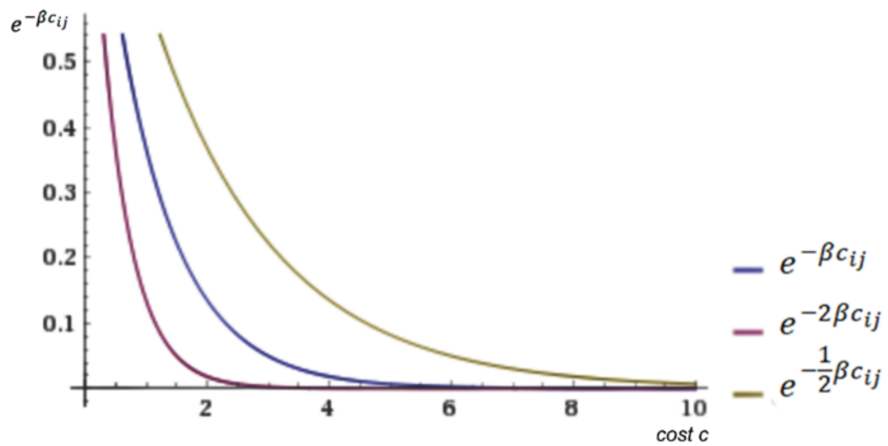
Finally, in order to incorporate competition effects, the ratio between the supply potential of the area (O_j) (i.e. the number of opportunities within the zone considered or the number of the access points) and the demand potential (D_j) has been taken into account. Both the supply and the demand potential may change depending on the time in which the analysis is conducted (e.g. the supply potential might be different in working days or in the week-end) and on the area involved (e.g. different areas present a different demand).

The resulting formula has the following form:

$$A_j(t,s) = \frac{AV_{ij} \times \sum_{j=1}^{n} \frac{O_j}{D_j} e^{-\beta c_{ij}}}{TVC \times \frac{V}{C} \times T_{ij} \times L_{ij}} \qquad (9)$$

where

[i] is the origin area and [j] is the destination area, $A_j(t,s)$ is the total accessibility of [j], AV_{ij} is the average travel speed from [i] to [j], TVC is the Traffic Volume Count parameter, (V/C) is the Volume-to-Capacity Ratio, T_{ij} is the travel time from [i] to [j], L_{ij} is the travel length from [i] to [j], O_j/D_j is the potential supply over demand ratio for zone [j], β is the cost elasticity parameter and c_{ij} is the travel cost between [i] and [j].



Graph 2 – Examples of fluctuations of the cost parameter depending on ß and the cost value.

In this index the key element is the cost parameter. Indeed, assuming all the other parameters constant in a selected time and area, the fluctuation of the cost parameter may introduce a proportional variation in the overall value of accessibility.

For example, in Graph 2 some fluctuations of the cost parameter depending on the cost value and β are shown. As the cost varies and assuming a constant β within the curve, the resulting $e^{-\beta c_{ij}}$ is a downward sloping curve as the blue one. However, if β is doubled the cost parameter will be $e^{-2\beta c_{ij}}$; in this case, the result will be a steeper downward sloping curve than the previous one, as the purple curve. On the other hand, if β is halved, the cost parameter will be $e^{-\frac{1}{2}\beta c_{ij}}$ and the resulting curve will have a flatter shape, as the green one.

Therefore, the cost parameter is structured in a way that makes possible to consider different degrees of demand elasticity within a specific segment of mobility demand. On the other hand, the elasticity of demand among different segments is expected to be very high. Thus, such parameter is not appropriate to express the marginal decrease in cost sensitivity in those cases were demand elasticity is very heterogeneous.

It is interesting to observe the outcomes of the costs fluctuations on accessibility, since they might be due to many external factors, such as changes in cost policies, taxation, or market fluctuations.

The next paragraph will show the use of the above Accessibility Index in a real environment, underlining its strengths and weaknesses and evaluating the obtained results.

4.2 Method and Data

In this paragraph we are going to test the Accessibility Index in a real situation. In order to pursue this objective, we implemented the following steps:

1. Identification of attractors: three attractors have been carefully chosen according to different characteristics. First, The London Eye has been selected because it is the most famous paid tourist attractions in the United

Kingdom. Moreover, it is one of the most well-known symbols in the current pop culture. The London Eye is located on the South Bank of the River Thames, in the Lambeth borough. It is placed in the city centre beside the Westminster Bridge, near to many of the most important London's iconic places, such as the Big Ben, County Hall and Westminster Abbey.

Second, the Royal Free Hospital has been selected, since it is a place of interest in the Metropolitan Borough of Hampstead. Even if it is relatively far off the city centre, the Royal Free Hospital is located in one of the richest residential neighbourhood in the London area and it is well connected to the city centre. Hampstead is also known for the cultural associations and attractions and for Hampstead Heath, a big park beside the Royal Free Hospital.

Third, the Brandenburg Gate has been selected because it is the most popular monument in Berlin and a symbol of the European history. It is located in the city centre, in the west side of Pariser Platz, and it represents the monumental entry to Unter den Linden, the boulevard which led to the Berlin City Palace.

2. Selection of an area of attraction (isochrone): since the Accessibility Index is affected by time and space variations, it was important to set a specific area of attraction. Therefore, a travel time of thirty minutes has been selected and isochrones for each attractor at 7:30 a.m. were drawn. The isochrones were defined by overlapping the city maps with the ones of the areas reachable in at most thirty minutes. The employed sources were Travel Time Platform and Google Maps.
3. Measurement of the index: by considering the outcomes obtained in point 2, the Accessibility Index has been calculated for each attractor. The data sources employed were the London's Department for Transport official

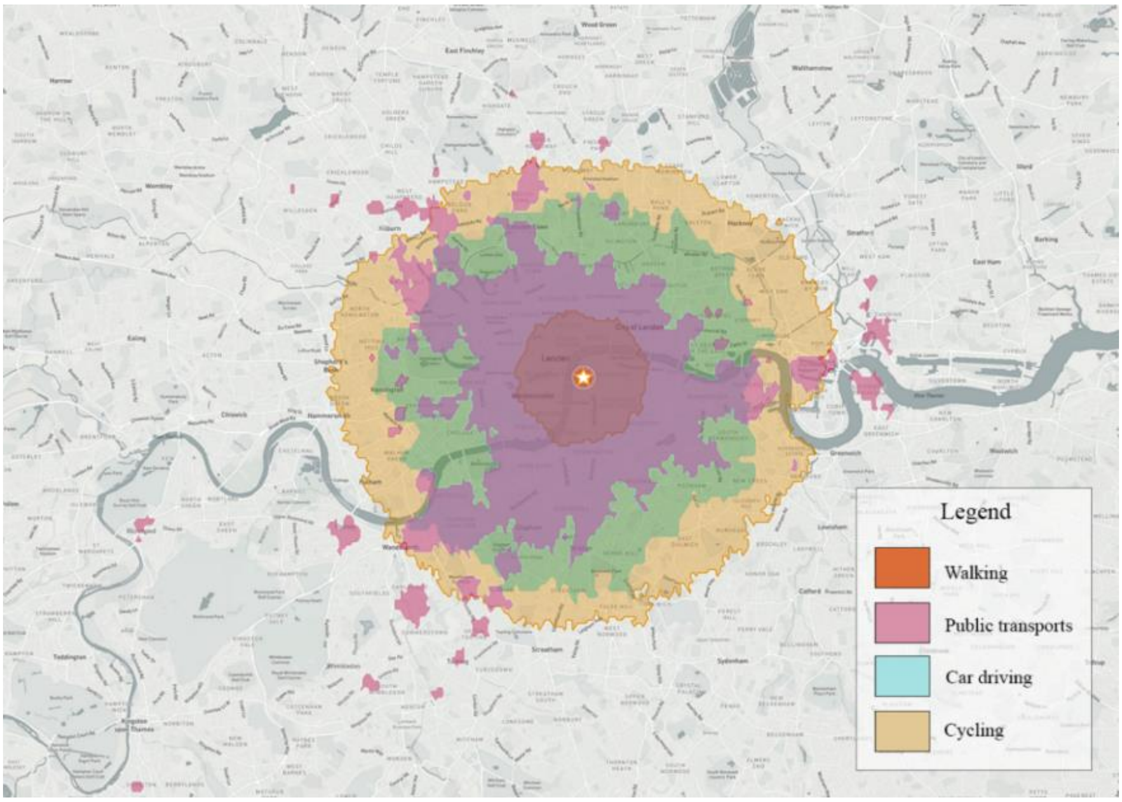
website, "London Datacentre" website, the official London's public transport website "Transport for London" and "Citymapper" website for the London's cases. Moreover, Berlin's data were gathered on the German "Federal Highway Research Institute" website, the German Statistics Federal Bureau website and the Berlin's official online website. The information about population composition were collected from "City Population" website.

After having explained the indicator's characteristics and the methodology used, we will present more in-depth the empirical application in a real environment.

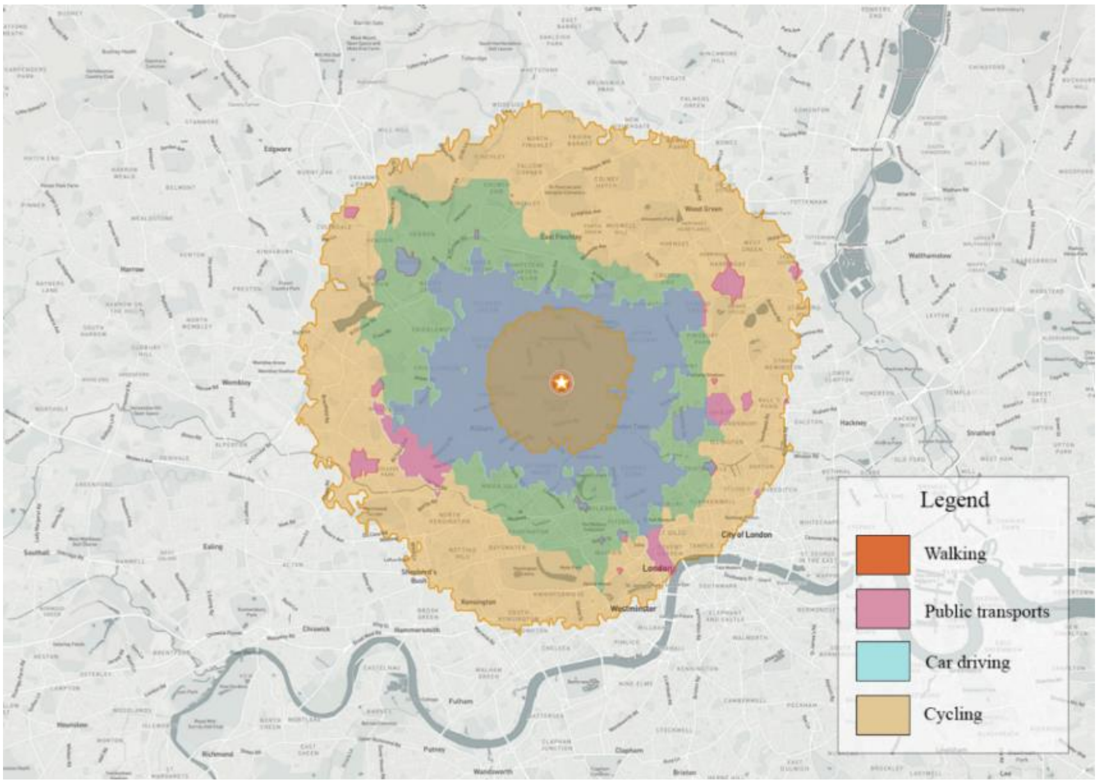
The main strength of the proposed Accessibility Index is the ability to represent theoretically the balance between more simplified approaches and complex models. The index is relatively versatile, therefore it may be used to compute accessibility using different transport systems, such as driving, cycling, walking or using the public transport.

As said at the beginning of the paragraph, we started setting the location and time in which the analysis will take place. We selected some points of interest as "attractors" according to different characteristics of the considered location (e.g. city centre vs hinterland); then, we fixed a specific time of the day, according to the fact that we wanted to evaluate accessibility for commuters during rush hour.

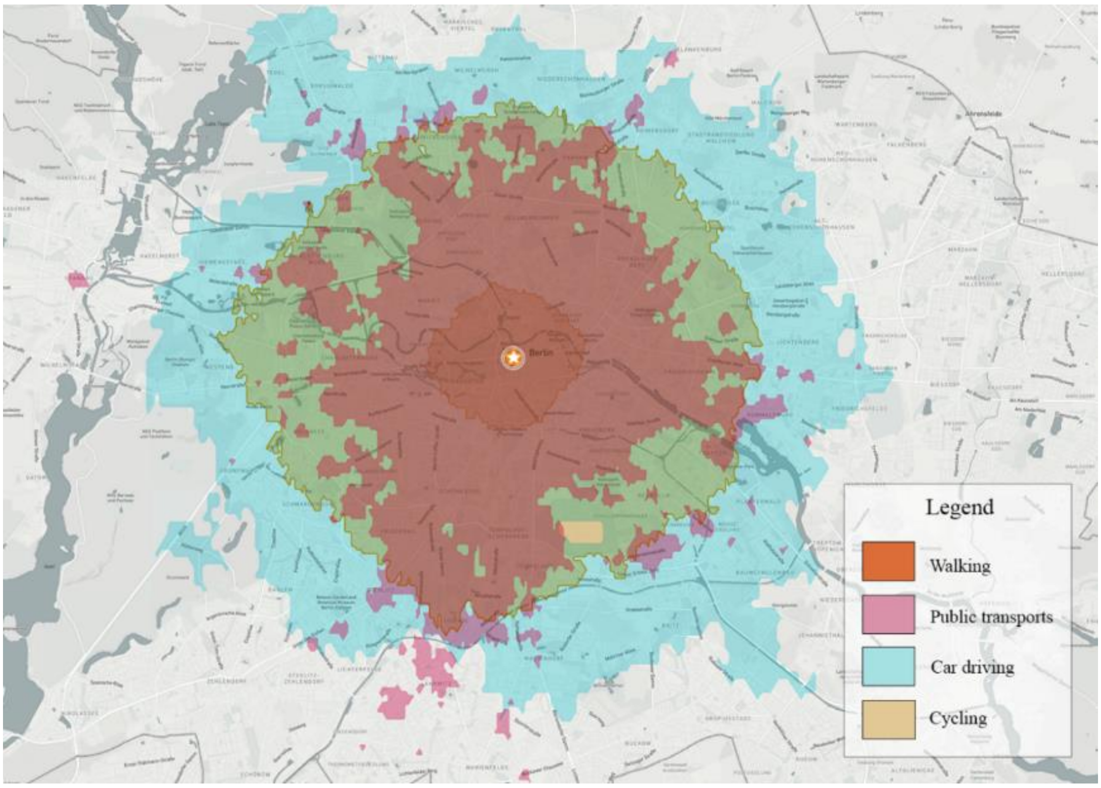
After that, we drew isochrones around the selected attractors for each different travel system (car driving, public transport, cycling ad walking) at the selected time, taking into account a thirty-minute total travel time. We selected a travel time of thirty-minutes according to the Marchetti's constant, which affirms that usually people are willing to spend a budget of one hour per day commuting. Therefore, the dimension of the reachable area depends on the transport system used to commute (Marchetti, 1995).



Graph 3a – Isochrones for different transport systems centred at The London Eye. Source: Travel Time Platform. Powered by Leaflet. ©OpenStreetMap. Created with TravelTime API. Places data provided by Foursquare. <https://app.traveltimeplatform.com>



Graph 3b – Isochrones for different transport systems centred at the Royal Free Hospital. Source: Travel Time Platform.



Graph 3c – Isochrones for different transport systems centred at the Brandenburg Gate. Source: Travel Time Platform.

It is possible to observe that for each different transport system, the thirty-minute isochrone will cover a different area of the map, due to the different maximum speed of the vehicle, road performances, etc. In particular, the shape of the isochrone helps us to understand the homogeneity level of the coverage of the transport system in analysis. Graphs 3a, 3b and 3c show that isochrones representing the public transport system are the more uneven, while the others tend to be more circular. This is a key point in evaluating accessibility, since a strongly irregular isochrone might produce important consequences, such as social exclusion or depopulation.

As said before, the Accessibility Index may be used to compute accessibility for different transport systems and in different time slots. In particular, we decided to run the empirical application considering commuters at 7:30 a.m. using the public transport system. The index has been used to measure accessibility for the given attractors in two different situations:

- *Scenario 1*: we considered two different attractors within the same city, we computed the Accessibility Index and we compared the results. In particular, we selected The London Eye, the iconic Ferris wheel in the city centre, and the Royal Free Hospital, a hospital born to provide free care to people with little means.
- *Scenario 2*: we selected two similar attractors in different cities, then we calculated the Accessibility Index and compared the results. In this case, we compared The London Eye to the Brandenburg Gate in Berlin, since both are iconic symbols of their cities and they are located in the city centre.

After having specified the attractors, the isochrones have been drawn according to the premises of the study, therefore assuming that:

- the attractor is located in the centre of the isochrone;
- isochrones represent the public transport system;
- isochrones have been calculated at 7:30 a.m.;
- isochrones show a radius of thirty minutes travel time departing from the central point.

Given a fixed time (t = 7:30 a.m.) and location (s = The London Eye *or* Royal Free Hospital *or* Brandenburg Gate), the general Accessibility Index formula in equation (9) can be simplified as follows:

$$A_j = \frac{AV_{ij} \times \sum_{j=1}^{n} \frac{O_j}{D_j} e^{-\beta c_{ij}}}{TVC \times \frac{V}{C} \times T_{ij} \times L_{ij}} \tag{10}$$

where

[i] is the origin area and [j] is the destination area, A_j is the total accessibility of [j], AV_{ij} is the average travel speed from [i] to [j], TVC is the Traffic Volume Count parameter, *(V/C)* is the Volume-to-Capacity Ratio, T_{ij} is the travel time from [i] to [j], L_{ij} is the travel length from [i] to [j], O_j/D_j is the potential supply over demand ratio for zone [j], β is the cost elasticity parameter and c_{ij} is the travel cost between [i] and [j].

The data required for calculations can be mainly obtained by mobility statistics or derived from mobility studies, such as Traffic Volume Count, Volume-to-Capacity Ratio, average speed, travel time and travel length. However, some data are not readily available and must be estimated. Indeed, the number of public transports stops has been used to calculate the potential supply and the population density has been used as a proxy for the potential demand.

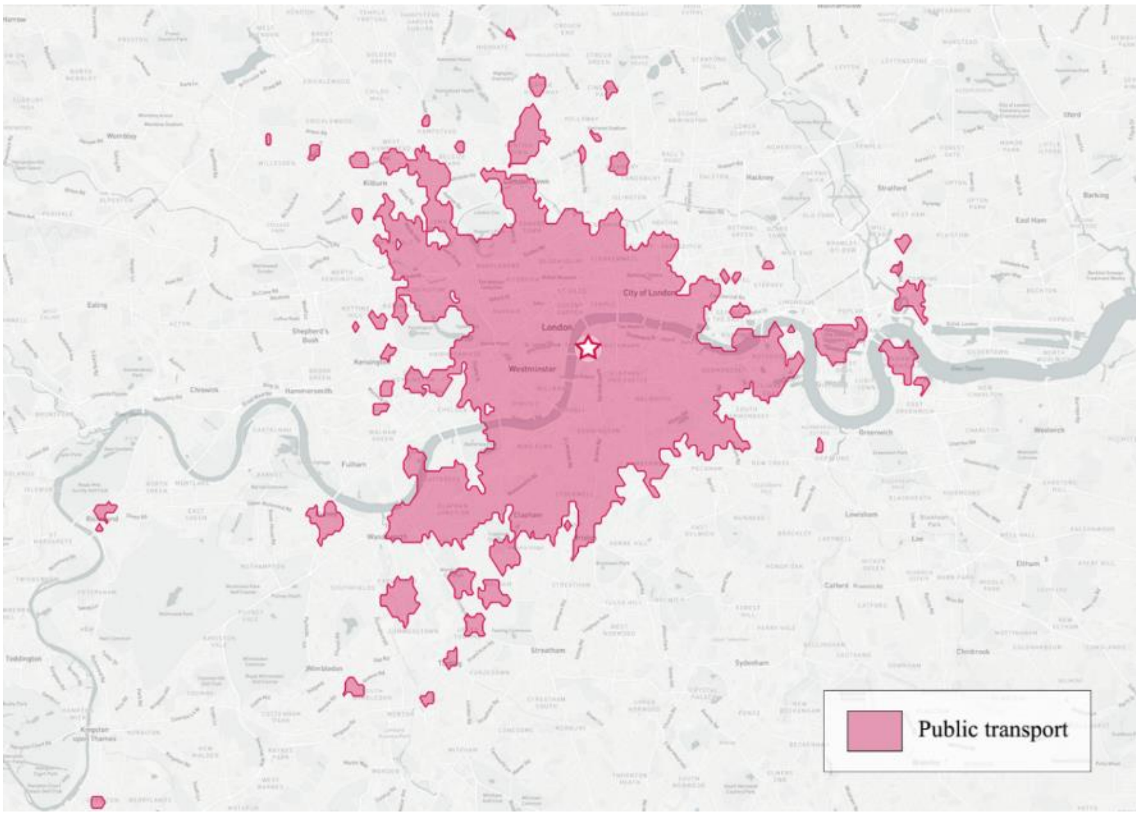
The next paragraphs will show the application of the Accessibility Index to each attractor taken into consideration, in order to evaluate their own accessibility level.

4.2.1 The London Eye

The first attractor we consider is The London Eye, located in London's city centre.

The majority of the data employed come from the London's Department for Transport and the London Datastore and refer to the current situation in 2017.

Given the formula in equation (10), it is possible to start the analysis.



Graph 4 – Public transport isochrone centred at The London Eye. Source: Travel Time Platform.

Since the isochrone is computed for a thirty-minute travel, $\overline{T_{ij}}$ is equal to 0.5. Starting from the estimation data of mobility statistics over the whole city of London, we estimate the median value of TVC, V/C, L_{ij} and AV_{ij}. Specifically, the annually TVC is equal to 29,539 million vehicle kilometres, that is an average of 1,690 thousand vehicles kilometres in half an hour per day.

V/C is assumed to be 85% in peak hours in urban centre, while the average travel length within the isochrone L_{ij} is equal to 8.5 km and AV_{ij} is equal to 28.32 km/h. The average travel length was calculated using the average distance reachable from the central point of the isochrone, excluding Surbiton station, which was considered an outlier.

Moreover, we decided to estimate the supply potential $\widehat{O_j}$ with the number of possible access points to the London Eye. In particular, we considered the public transport's stations far at most a five-minute walk, including bus, train and tram stations, tube and ferry terminals. Therefore, in this case $\widehat{O_J}$ is equal to 10.

On the other side, we defined the demand potential $\widehat{D_J}$ as the population density, which in Greater London is equal to 6,880 /km².

The average travel cost within the isochrone is equal to £1.95 or €2.23 for the public transport. Assuming the cost elasticity in London being equal to 0.4 (equation (11)) or 0.8 (equation (12)), the cost parameter will be equal respectively to $e^{-0.892}$ or $e^{-1.784}$.

Assuming $e = 2.71828$, the values above were substituted into the simplified equation (10). The formula will have the following form:

$$A_L = \frac{AV_{iL} \times \sum_{L=1}^{n} \frac{\widehat{O_L}}{\widehat{D_L}} e^{-\beta c_{iL}}}{TVC \times \frac{V}{C} \times \overline{T_{iL}} \times L_{iL}} = \frac{28.32 \times \frac{10}{6{,}880} e^{-0.892}}{1{,}690 \times 0.85 \times 0.5 \times 8.5} \cong 2.76324 \times 10^{-6} \quad (11)$$

$$A_L = \frac{AV_{iL} \times \sum_{L=1}^{n} \frac{\widehat{O_L}}{\widehat{D_L}} e^{-\beta c_{iL}}}{TVC \times \frac{V}{C} \times \overline{T_{iL}} \times L_{iL}} = \frac{28.32 \times \frac{10}{6{,}880} e^{-1.784}}{1{,}690 \times 0.85 \times 0.5 \times 8.5} \cong 1.13247 \times 10^{-6} \quad (12)$$

where

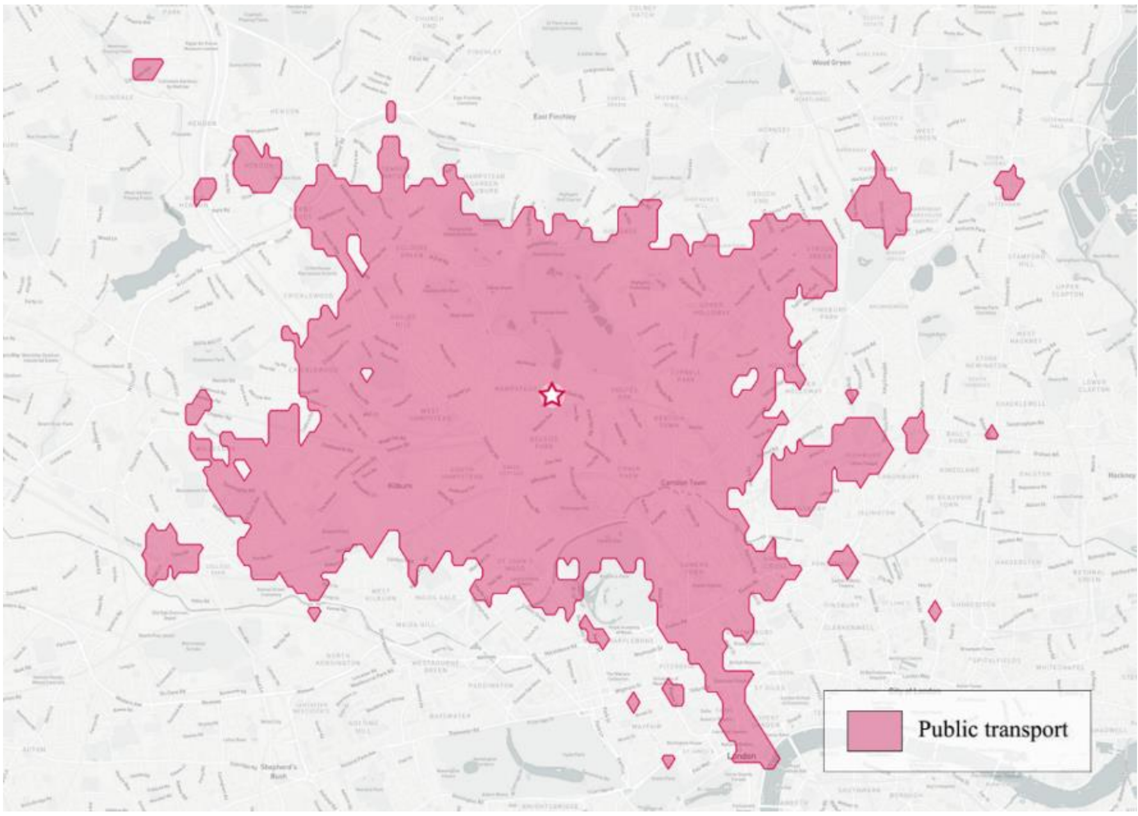
[i] is the point of origin within the isochrone and [L] is The London Eye, A_L is the total accessibility of [L], AV_{iL} is the average travel speed from [i] to [L], TVC is the Traffic Volume Count parameter, (V/C) is the Volume-to-Capacity Ratio, T_{iL} is the travel time from [i] to [L], L_{iL} is the travel length from [i] to [L], O_L/D_L is the potential supply over demand ratio for zone [L], β is the cost elasticity parameter and c_{iL} is the travel cost between [i] and [L].

4.2.2 Royal Free Hospital

The second attractor is the Royal Free Hospital, located in the hinterland but not so far from London's city centre.

As in The London Eye's case the data for this analysis come mainly from the London's Department for Transport and the London Datastore and refer to the current situation in 2017.

Now, using the formula in equation (10), we will start the analysis of the Royal Free Hospital case.



Graph 5 – The public transport isochrone centred at the Royal Free Hospital. Source: Travel Time Platform.

Since the isochrone is computed for a 30-minute travel, $\overline{T_{ij}}$ is equal to 0.5. We estimate the average value of TVC, V/C, L_{ij} and AV_{ij} by using the estimation data of mobility statistics of London. In particular, TVC is equal to 1,690 thousand vehicles kilometres, V/C is assumed to be equal to 75%, L_{ij} is equal to 4.85 km and AV_{ij} is equal to 28.32 km/h.

Moreover, we decided to estimate the supply potential $\widehat{O_j}$ with the number of possible access points to the Royal Free Hospital. As in The London Eye case, we considered the public transport's stations far at most a five-minute walk. Therefore, $\widehat{O_J}$ is equal to 13.

On the other side, we defined the demand potential $\widehat{D_J}$ as the population density, which in London is equal to 6,880 /km^2.

The average travel cost within the isochrone is equal to £2.70 or €3.08 for the public transport. Assuming the cost elasticity in London being equal to 0.4 (equation (13)) or 0.8 (equation (14)), the cost parameter will be equal respectively to $e^{-1.232}$ or $e^{-2.464}$.

Substituting the values into the simplified equation (10) and assuming $e = 2.71828$, the formula will have the following form:

$$A_R = \frac{AV_{iR} \times \sum_{R=1}^{n} \frac{\widehat{O_R}}{\widehat{D_R}} e^{-\beta c_{iR}}}{TVC \times \frac{V}{C} \times \overline{T_{\iota R}} \times L_{iR}} \cong 5.07852 \times 10^{-6} \qquad (13)$$

$$A_R = \frac{AV_{iR} \times \sum_{R=1}^{n} \frac{\widehat{O_R}}{\widehat{D_R}} e^{-\beta c_{iR}}}{TVC \times \frac{V}{C} \times \overline{T_{\iota R}} \times L_{iR}} \cong 1.48144 \times 10^{-6} \qquad (14)$$

where

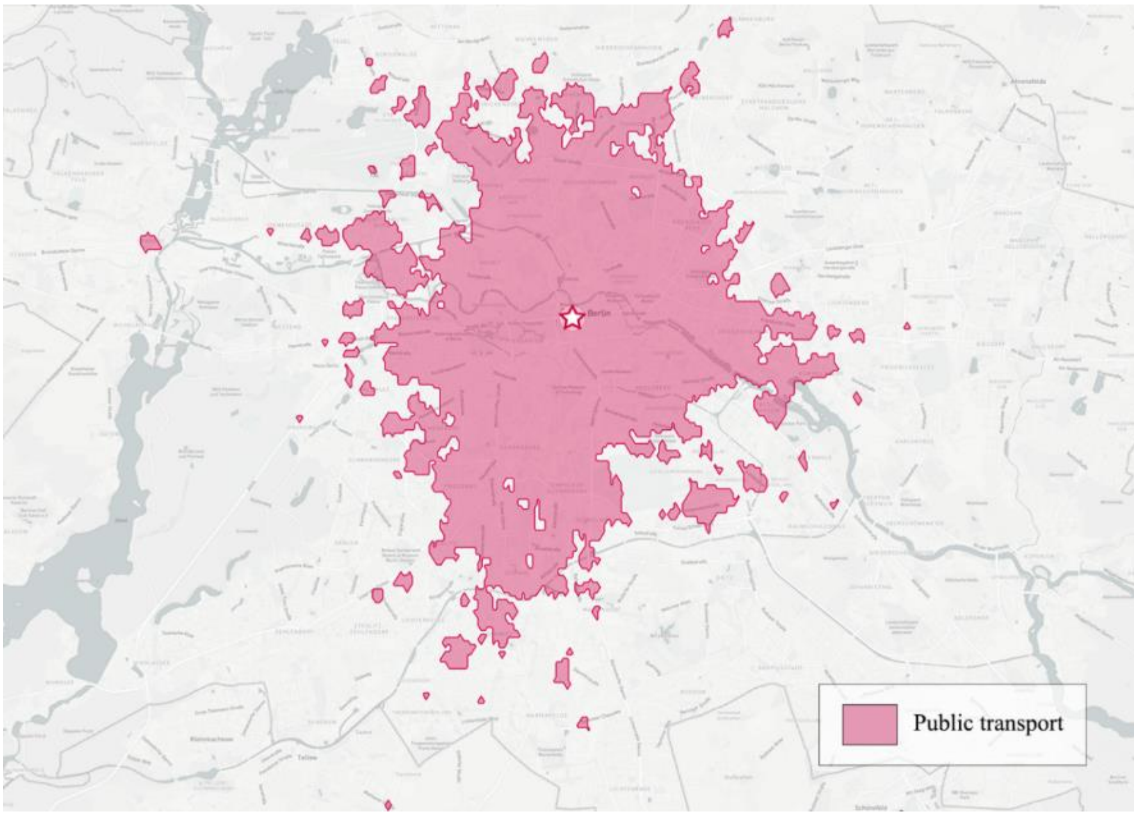
[i] is the point of origin within the isochrone and [R] is the Royal Free Hospital, A_R is the total accessibility of [R], AV_{iR} is the average travel speed from [i] to [R], TVC is the Traffic Volume Count parameter, (V/C) is the Volume-to-Capacity Ratio, T_{iR} is the travel time from [i] to [R], L_{iR} is the travel length from [i] to [R], O_R/D_R is the potential supply over demand ratio for zone [R], β is the cost elasticity parameter and c_{iR} is the travel cost between [i] and [R].

4.2.3 Brandenburg Gate

The third attractor considered in this paper is the Brandenburg Gate, the most famous Berlin's landmark, which is located in the city centre.

The majority of the data employed come from the German Federal Highway Research Institute, the German Statistics Federal Bureau and from the Berlin's official online website, and refer to the current situation in 2017. In this case, when some data were not available, we decided to use a benchmark information.

Given the formula in equation (10), it is possible to start the analysis for the last of the selected attractors.



Graph 6 – The public transport isochrone centred at the Brandenburg Gate. Source: Travel Time Platform.

Since the isochrone is computed for a 30-minute travel, $\overline{T_{ij}}$ is equal to 0.5. Starting from the estimation data of mobility statistics of Berlin when available or of the whole Germany, we estimate the median value of TVC, V/C, L_{ij} and AV_{ij}. Specifically, TVC is equal to 934 thousand vehicles in half an hour and we assume V/C equal to 80% in rush hours. L_{ij} is equal to 9.99 km and AV_{ij} is equal to 24.90 km/h.

Moreover, we decided to estimate the supply potential $\widehat{O_J}$ with the number of possible access points to the Brandenburg Gate. In particular, we considered the public transport's stations far at most a five-minute walk. Therefore, $\widehat{O_J}$ is equal to 5.

On the other side, we defined the demand potential $\widehat{D_J}$ as the population density, which in Berlin is equal to 4,055 /km^2.

The average travel cost for the public transport within the isochrone is equal to €3.40. Assuming the cost elasticity in Berlin being equal to 0.4 (equation (15)) or 0.8 (equation (16)), the cost parameter will be equal respectively to $e^{-1.36}$ or $e^{-2.72}$.

Substituting the values into the simplified equation (10) and assuming $e = 2.71828$, the formula will have the following form:

$$A_B = \frac{AV_{iB} \times \sum_{B=1}^{n} \frac{\widehat{O_B}}{\widehat{D_B}} e^{-\beta c_{iB}}}{TVC \times \frac{V}{C} \times \overline{T_{iB}} \times L_{iB}} \cong 2.11137 \times 10^{-6} \qquad (15)$$

$$A_B = \frac{AV_{iB} \times \sum_{B=1}^{n} \frac{\widehat{O_B}}{\widehat{D_B}} e^{-\beta c_{iB}}}{TVC \times \frac{V}{C} \times \overline{T_{iB}} \times L_{iB}} \cong 0.5419 \times 10^{-6} \qquad (16)$$

where

[*i*] is the point of origin within the isochrone and [*B*] is he Brandenburg Gate, A_B is the total accessibility of [*B*], AV_{iB} is the average travel speed from [*i*] to [*B*], *TVC* is the Traffic Volume Count parameter, *(V/C)* is the Volume-to-Capacity Ratio, T_{iB} is the travel time from [*i*] to [*B*], L_{iB} is the travel length from [*i*] to [*B*], O_B/D_B is the potential supply over demand ratio for zone [*B*], β is the cost elasticity parameter and c_{iB} is the travel cost between [*i*] and [*B*].

4.3 Two Scenarios for Comparisons Between Different Attractors

On the basis of the results obtained in the previous paragraph, we are going to compare the accessibility levels of the selected attractors in the defined scenarios. For convenience, Table 2 summarises the outcomes of equations (11), (12), (13), (14), (15) and (16).

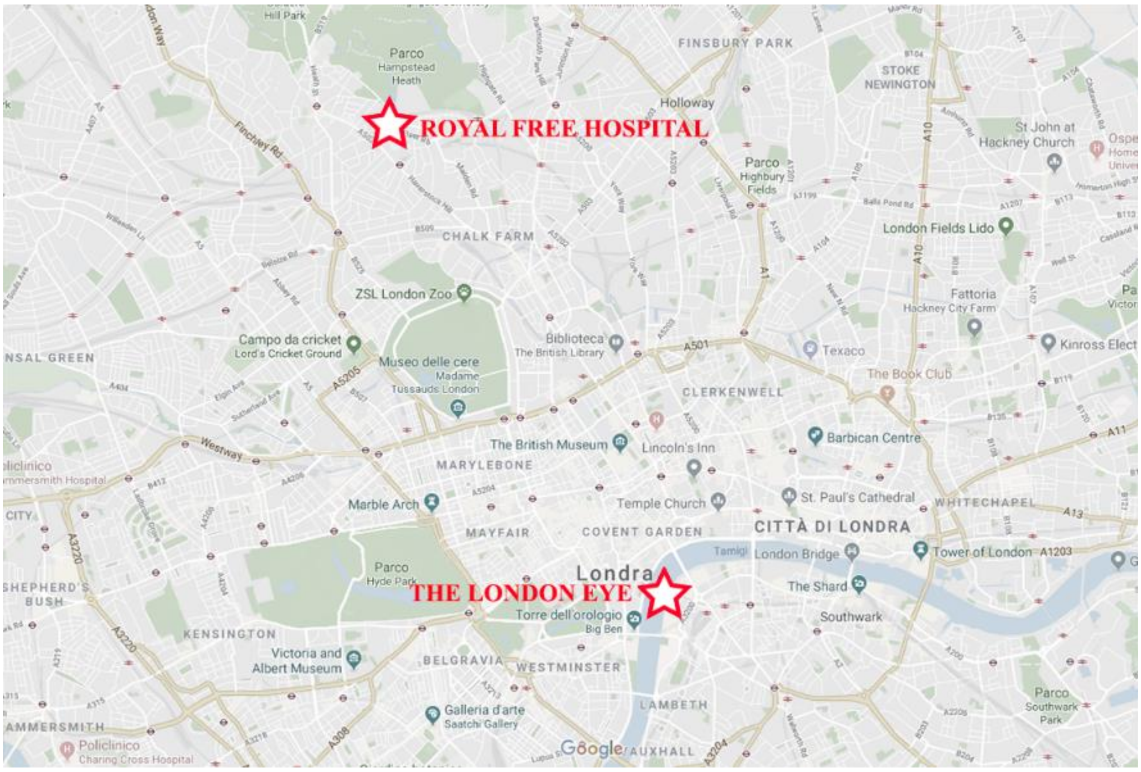
	$\boldsymbol{\beta = 0.4}$	$\boldsymbol{\beta = 0.8}$
THE LONDON EYE	$A_L = 2.76324 \times 10^{-6}$	$A_L = 1.13247 \times 10^{-6}$
ROYAL FREE HOSPITAL	$A_R = 5.07852 \times 10^{-6}$	$A_R = 1.48144 \times 10^{-6}$
BRANDENBURG GATE	$A_B = 2.11137 \times 10^{-6}$	$A_B = 0.5419 \times 10^{-6}$

Table 2 – Accessibility values for The London Eye, the Royal Free Hospital and the Brandenburg Gate.

4.3.1 Scenario 1: The London Eye vs The Royal Free Hospital

The first scenario proposed is the comparison of the accessibility level of two different attractors in the same city.

We chose the city of London, since it presents a well-developed transport system and many related data are available. Then, we selected a notorious attractor in the city centre, The London Eye, and another attractor slightly at the edge of the urban centre, the Royal Free Hospital (Graph 7).



Graph 7 – Locations of The London Eye and the Royal Free Hospital with respect to the city centre. Source: Google Maps.

In paragraph 4.2 we explained how we calculated the level of accessibility for both the attractors. Now, we will compare the accessibility of The London Eye (A_L) with respect to the accessibility of the Royal Free Hospital (A_R).

In Table 3 have been summarised the data employed in computations and the results obtained for each attractor.

	The London Eye		Royal Free Hospital	
AV_{ij}	28.32 km/h		28.32 km/h	
O_j	10		13	
D_j	6,880 / km^2		6,880 / km^2	
C_{ij}	€2.23		€3.08	
TVC	1,690		1,690	
V/C	85%		75%	
T_{ij}	0.5		0.5	
L_{ij}	8.50 km		4.85 km	
ß	0.4	0.8	0.4	0.8
A_j	2.76324 x 10^{-6}	1.13247 x 10^{-6}	5.07852 x 10^{-6}	1.48144 x 10^{-6}

Table 3 – Accessibility levels computed for The London Eye and the Royal Free Hospital.

For $ß = 0.4$, $A_L < A_R$ hence, The London Eye exhibits a lower accessibility than the Royal Free Hospital.

Looking at the collected data, we can see that the main differences between the two attractors are the congestion level and the average travel length. Indeed, The London Eye is located in the city centre, where the traffic is high and the congestion is stronger than in the hinterland. Moreover, the average travel length in The London Eye isochrone is nearly doubled with respect to the Royal Free Hospital one. This means that the public transport has a higher distance coverage in the centre, since it is possible to reach very far locations. However, the greater travel length means also that when starting a journey from a random point within the isochrone, the attractor is much farther to reach on average. Therefore, as we said in paragraph 4.1, the total accessibility decreases as the travel length increases.

Another difference is in the number of access point to the attractor. In fact, the Royal Free Hospital exhibits a greater number of public transport station nearby than The London Eye, revealing to be well-connected through the transport system. Even if the difference is minimal, the information affects the overall accessibility level, increasing the final result.

Finally, it is important to observe that The London Eye presents lower average costs than the Royal Free Hospital. Indeed, the cost for the public transports is cheaper in the city centre than in the hinterland. However, lower travel costs affect marginally the total accessibility and are not able to fill the gap created by the worse performances in some of the others indexes. After all, we assumed a highly inelastic cost sensitivity with β equal to 0.4.

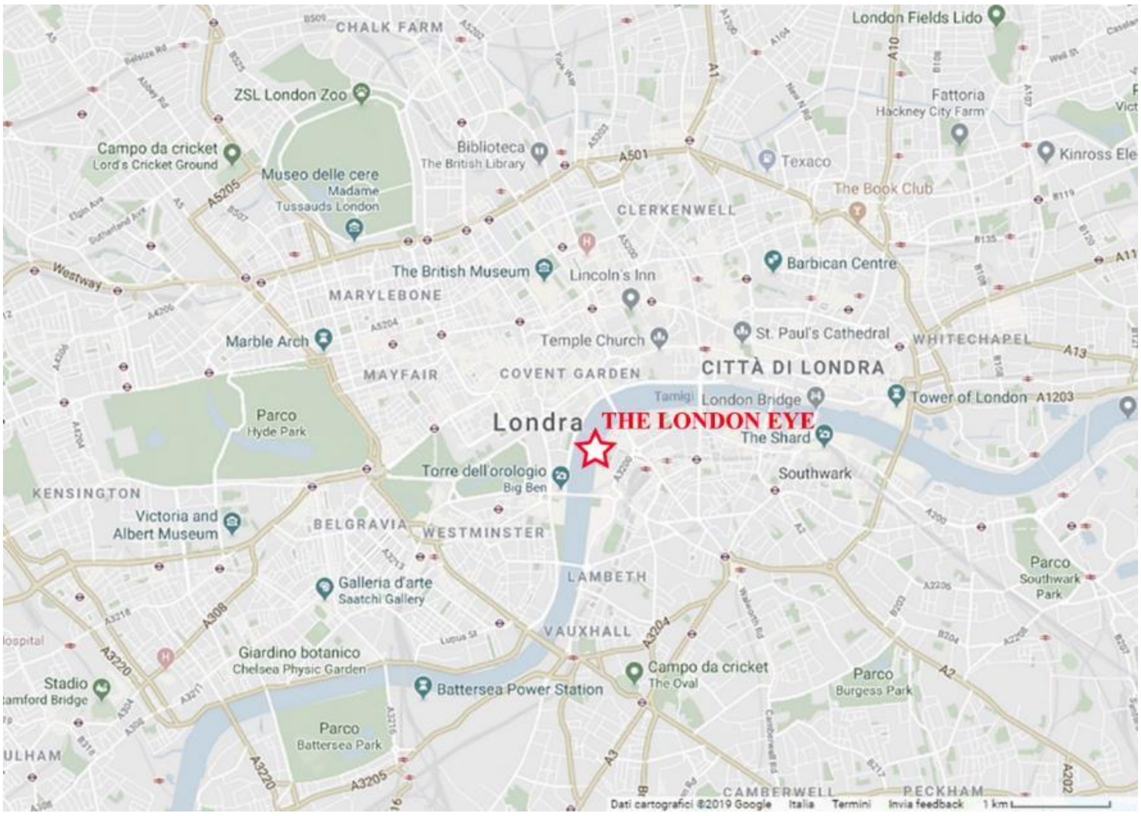
For $\beta = 0.8$, $A_L < A_R$ hence, The London Eye still exhibits a lower accessibility than the Royal Free Hospital. Thus, despite the different values of β, the overall accessibilities show the same behaviour. This information is useful in order to evaluate to which extent the changes in the cost parameter affect the accessibility value for a given location. Indeed, we can see how an increase in the cost elasticity parameter, which is higher but still inelastic, produces a stronger decrease in the overall accessibility of the Royal Free Hospital than in the one of The London Eye. However, in this case, the difference in the travel cost is not enough to change the result of the whole analysis.

The comparison between the data collected for The London Eye and the Royal Free Hospital confirms the result obtained with the proposed Accessibility Index, which sees the Royal Free Hospital more accessible than The London Eye.

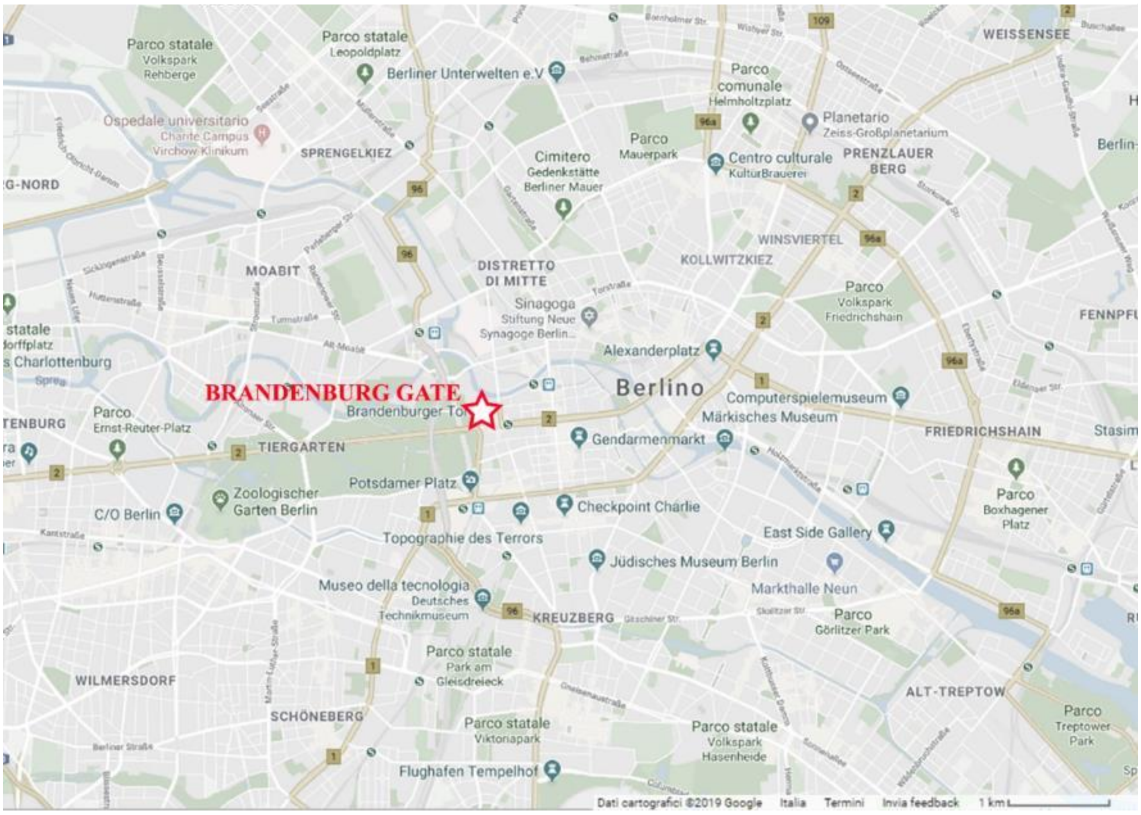
4.3.2 Scenario 2: The London Eye vs the Brandenburg Gate

The second scenario we propose compares the accessibility level of two similar attractors located in different cities.

We chose The London Eye, in London (Graph 8a), and the Brandenburg Gate, in Berlin (Graph 8b). Both the attractors are located in the city centre in two cities where the public transports are well-developed and provide a good coverage.



Graph 8a – The location of The London Eye with respect to the city centre. Source: Google Maps.



Graph 8b – The location of the Brandenburg Gate with respect to the city centre. Source: Google Maps.

In paragraph 4.2 we explained how we calculated the level of accessibility both for The London Eye and the Brandenburg Gate. Now, we will compare the accessibility of The London Eye (A_L) with respect to the accessibility of the Brandenburg Gate (A_B).

The data employed in computations and the results obtained for each attractor are summarised in Table 4.

	The London Eye		Brandenburg Gate	
AV_{ij}	28.32 km/h		24.90 km/h	
O_j	10		5	
D_j	6,880 / km^2		4,055 / km^2	
C_{ij}	€2.23		€3.40	
TVC	1,690		934	
V/C	85%		80%	
T_{ij}	0.5		0.5	
L_{ij}	8.50 km		9.99 km	
β	0.4	0.8	0.4	0.8
A_j	2.76324 x 10^{-6}	1.13247 x 10^{-6}	2.11137 x 10^{-6}	0.5419 x 10^{-6}

Table 4 – Accessibility levels computed for The London Eye and the Brandenburg Gate.

Comparing the resulting accessibility levels, we can see that for $ß = 0.4$, $A_L > A_B$, meaning that The London Eye is more accessible than the Brandenburg Gate.

Looking at the collected data, we will evaluate the reliability of the results. Note that the average speed is slightly higher in London than in Berlin.

The first noticeable difference is in the number of the access points to the respective attractor. Indeed, even if the two attractors are both in the city centre, the Brandenburg Gate exhibits half The London Eye's public transport stations nearby. At the same time, Berlin's population density is lower than the London one. Therefore, there is an overall decrease in the potential supply over demand ratio, that results in a decrease in the total level of accessibility.

Furthermore, the average travel length is greater within the Brandenburg Gate's isochrone than in The London Eye's one. As we said before, a longer travel length contributes in decreasing the overall accessibility level.

On the other hand, statistics about traffic and congestion are lower in Berlin than in London. In particular, the Brandenburg Gate's TVC is strongly lower than The London Eye's one, producing an increase in accessibility. Moreover, the congestion percentages of the two attractors are similar, but Berlin still exhibits a better performance. Of course, this will affect accessibility, increasing it.

Finally, the public transport costs in the centre of Berlin are much higher than in the centre of London. However, as well as in Scenario 1, the cost elasticity presents an inelastic behaviour for public transport, therefore, an increase in costs will not produce a strong impact on the overall accessibility. Nevertheless, Berlin's higher costs contribute to decrease the accessibility total value.

For $ß = 0.8$, $A_L > A_B$, meaning that the increase in the cost elasticity parameter did not affect the final result of the analysis. This is probably due to the fact that both the elasticity parameters considered represent an inelastic cost behaviour.

It is interesting to observe that the difference in the variation between the overall accessibilities for $ß = 0.4$ and $ß = 0.8$ are similar. This might be due to the fact that the two attractors are located in the city centre and the total accessibility is not strongly affected by the travel cost.

Comparing two attractors in two different cities is useful to evaluate how fluctuations in the single components of the Accessibility Index affect the final result. We showed that, using a simple indicator like the one proposed in this experiment, the trade-offs between the parameters are still unambiguous and directly affect the accessibility level. Evaluating the data gathered to compare the two attractors it is possible to further study the magnitude of the fluctuations to see in which percentage it affects the final value. Finally, the Accessibility Index results confirm the expectations to have basically a similar accessibility level for two similar situations.

The next paragraph will introduce a further development of the Accessibility Index, in order to give a more general representation of its benefits and usability.

4.4 A Possible Policy Goal

In paragraphs 4.1, 4.2 and 4.3 we tried to make a proposal for an accessibility indicator able to take into account different predefined parameters, and we use it to analyse accessibility for different attractors.

In running the empirical application, an important assumption has been done: all the parameters involved in the computation of the Accessibility Index had the same significance within the formula, therefore, the same impact on the final result.

Actually, each parameter might acquire a different weight, resulting more or less important in determining the total accessibility value. The weight of each of the *n* parameter will be indicated as $\mu_{1,\ \ldots,\ n}$. Thus, weighting the parameters, the formula in equation 9 will have the following form:

$$A_j(t,s) = \frac{\mu_1 AV_{ij} \times \sum_{j=1}^{n} \mu_{2,j} \frac{O_j}{D_j} e^{-\mu_3 \beta c_{ij}}}{\mu_4 TVC \times \mu_5 \frac{V}{C} \times \mu_6 T_{ij} \times \mu_7 L_{ij}} \qquad (17)$$

The weighted Accessibility Index in equation (17) has several applications. First, weighting the singular parameters means that it is possible to evaluate how the indicator reacts to the fluctuations of the single parameters, according to their sensitivity. Indeed, if it has been decided that the V/C Ratio has a more significant impact on the index than the other parameters, it is possible to highlight the congestion parameter just by increasing the value of its weight μ_5

(or decreasing the values of all the other μ_n). Moreover, it is possible to evaluate how to balance a change in one of the parameters in order to maintain at least the same accessibility level. For instance, this is the case when there is a strong increase in the travel costs and policy makers want to keep constant the accessibility level.

On the other side, the weighted indicator helps to understand how to increase or decrease the accessibility level of a given location changing the significance of one or more parameters, for example given the current mobility statistics. Therefore, in mobility planning and assessment, the weighted Accessibility Index might be used to measure how accessibility changes depending on urban planning. Seeing how new infrastructures may affect the accessibility for a given location and predict the fluctuations of the accessibility level due to a new transport system, represent a key point in mobility planning.

Moreover, the Accessibility Index may be used as a benchmark to evaluate the performance of the policy makers. Indeed, the indicator when weighted might represent an important policy tool, comparing the situation before and after a new transport strategy or re-organization in the transport system.

As we showed, the importance of the impact of accessibility on transport mobility is pretty straightforward. However, it is important to focus on the consequences that a lack of accessibility may produce in the social system and in the environment, too. In particular, is it possible to refer to social exclusion, degradation of suburban areas and depopulation problems. Having a weighted indicator as the Accessibility Index in equation 17 at disposal, means to be able to forecast not only the direct changes on mobility, but to have a broader view on many related issues. For instance, it is possible to estimate if and in which percentage an increase in travel costs will lead to a greater social exclusion of people of meager means. Moreover, it might be possible to evaluate if some urban and suburban area are degraded or depopulated due to an inefficient urban planning, and use the evidences collected to develop an efficient strategy.

Being able to effectively evaluate the transport system and, in particular, the accessibility, is a key point in the city's growth and progress, in order to trigger a sustainable development. After all, transportation is "the unifying principle of the world" (Marchetti, 1995).

Conclusions

The paper provides a solid background on the concept of accessibility through an overview of the existent literature, trying to capture the multifaceted nature of the problem. From the literature review it emerges that there is a strong, intrinsic heterogeneity that thoroughly pervades accessibility, also due to the plentiful fields of research involved.

In view of this heterogeneity and the evolution that accessibility experienced throughout the years, the holistic model developed by Geurs and Van Wee has been selected as a benchmark. This choice is due to the fact that the authors were able to summarise the many accessibility theories presented in a unique holistic model. However, it was explained how applying this model is extremely difficult, limiting the usefulness of the model itself. Moreover, the results of a such complex model are not only difficult to be obtained, but also to be evaluated and communicated. Therefore, we considered it appropriate to take a step back, trying to find an alternative solution to evaluate accessibility.

Consequently, the main aim of this paper is the proposal of an indicator of accessibility. The here proposed Accessibility Index is an experiment to figure out if it is possible to derive a unique indicator able to balance simplified theories and complex approaches. Therefore, after selecting some parameters that affect accessibility in many different ways, we derived an indicator that should increase in front of an increase in the accessibility level of the location, according to a greater effectiveness in the parameters used to describe it. The premises for the Accessibility Index were the following:

1. to be relatively easy to compute;
2. to be easy to evaluate without providing ambiguous results;
3. to be easy to communicate.

Then, the Accessibility Index was tested in a real environment, in order to evaluate the results and assess to which extent the final results reflected the true situation. The findings exhibit that the Accessibility Index provided a response reflecting to some extent the reality, confirming the expectations we had before running the analysis.

At that point, we considered of interest to demonstrate how the indicator might be use as a policy tool. Therefore, a weighted Accessibility Index was derived. The general weighted Accessibility Index has a broader application, since it permits to give a different weight to each parameter. This feature permit to run a more detailed analysis, specific for the environment in which it operates.

The proposed Accessibility Index encourages the policy makers to question on the effectiveness of the implemented mobility and urban strategies. It represents a policy instrument able to expand the vision of policy from a mere mechanistic perspective to a more holistic measure. Indeed, the indicator may allow to identify the more significant accessibility components, considering the parameters that were usually not analysed or were considered unimportant.

However, the indicator is an experiment and not an absolute benchmark since it presents some constraints. First of all, not all the data required are easily available and missing one or more parameter strongly affect the final result. Moreover, the travel costs are affected by the cost elasticity parameter, that may vary according to different locations, cultures, or period of time. In this experiment the cost elasticity parameter was considered to be constant since we selected specific areas with a similar urban development. Finally, there is not a detailed analysis on the statistical significance of the parameters included in the formula, therefore, we did not assess the relative importance of each parameter in the proposed indicator with respect to the final result.

Despite the limits of the proposed indicator, it may represent the starting point for further researches. First, it might be interesting to evaluate the relevance of each parameter inside the formula, trying to improve the reliability of the Accessibility Index. Consequently, some new parameters might be tested by adding them into the formula to evaluate if they are statistically significant or not. Moreover, it would be interesting to adjust the Accessibility Index for different social groups, in order to better evaluate how accessibility affects social problems such as the social exclusion.

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