Report developed for the IPTC Project - Improving Public Transport Competitiveness versus the Private Car

Using Accessibility Measures to reveal Public Transport Competitiveness compared to the car.

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Using Accessibility Measures to reveal

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1. **Preface**

This report was developed for the IPTC Project - Improving Public Transport Competitiveness versus the Private Car - by the Research Centre for Territory, Transports and Environment (CITTA) of the University of Oporto, Portugal - and coordinated by the Norwegian Institute of Transport Economics (TOI).

Within the tasks developed for the project, this report provides a literature review of the main accessibility instruments with potential to reveal the relative competitiveness between public transport and the private car. In the last section, we present a proposal of useful indicators that can easily be implemented in planning practice in order to support policies improving public transport competitiveness over the private automobile.

2. Introduction

Accessibility is a well-known concept in urban planning researcher that measures the ease with which the urban structure allows access to a variety of spatially dispersed opportunities (Silva & Pinho, 2010). Accessibility instruments consist of the operational form of accessibility measures (Silva C. , 2018) and are a type of Planning Support System (PSS) useful for supporting an integrated land-use and transport planning (Papa, Silva, te Brömmelstroet, & Hull, 2016). Such instruments can be applied to reveal the mobility potential allowed by the urban structure by providing knowledge on the different levels of urban accessibility by different transport mode at different scales. From the planning practice perspective, the use of accessibility instruments helps to identify inequalities in land-use and transport systems to assist the formulation of policies aiming to overcome them. Also, they are important tools useful to justify existing decisions, support strategy and development plans. However, such instruments have limited reach in planning practice (Boisjoly and El-Geneidy, 2017; (Silva, Bertolini, te Brömmelstroet, Milakis, & Papa, 2017).

A similar concern is revealed in the accessibility instrument literature (Straatemeier, 2008; Benenson, Martens, Rofé, & Kwartler, 2011; Bertolini, Hull, Papa, Silva, & Ruiz, 2019). In planning practice, the concept of mobility, based on infrastructure, has been widely prioritized over accessibility concepts. The literature identifies two issues that move the PSS away from the practical field, revealing its challenge in accepting and using such planning support tools. One is related to increased scientific rigour over the past decades and, the other, based on the ever-growing technological improvements. This argument is held by some authors regarding the PSS developers' concern in pursuit accurate and detailed tools supported by the academic field and allowed by technological support, leading to building increasingly complex and sophisticated instruments.

Accessibility has been extensively researched in the last decades. There was a tendency by the researchers in pursuing accuracy to estimate travel demand that better represents real-life conditions. The variety of GIS tools designed to collect a large amount of data (to enable accurate forecasting of travel demand) is seen as a technical improvement but have operational limitation in planning practice. The technological apparatus needed for running complex accessibility instruments requires not only specific knowledge but also financial willingness (Straatemeier, 2008; Benenson, Martens, Rofé, & Kwartler, 2011; Bertolini, Hull, Papa, Silva, & Ruiz, 2019).

The scientific rigour is related to the introduction of various components to measure accessibility such as transport, land-use, temporal and individual aspects (Geurs & van Wee, 2004; Geurs & van Eck, 2001). Therefore, accessibility instruments are designed assuming different

levels of complexity depending on the use of one or a combination of these components in different types of approaches. Such comprehensive accessibility measures also require increased skills from practitioners (Straatemeier, 2008) and, as a result, the studies tend to remain in the academic field instead of efficiently support planning decisions (Benenson, Martens, Rofé, & Kwartler, 2011). Thus, on the one hand, the PSS developers (researchers) have built complex and sophisticated instruments that better represent real-life conditions with the necessary technological assist. On the other, the potential users (practitioners) are generally unaware of their potential and inexperienced to use them as Planning Support Tools. The lack of knowledge from planning practitioners seems to be an important factor to reduce their intention to use such decision support tools, as well as their willingness to afford technological devices to run those instruments. There is a dilemma between rigour and relevance of such instruments since who develops them does not necessarily use them in practice (Silva, Bertolini, te Brömmelstroet, Milakis, & Papa, 2017; te Brömmelstroet, Curtis, Larsson, & Milakis , 2016). Also, accessibility is a complex and multi-dimensional concept misunderstood by practitioners, which itself already contributes to the legibility of such instruments often seen as complex, inflexible and incomprehensible (Papa, Silva, te Brömmelstroet, & Hull, 2016). Given the increasing acknowledgement and interest in accessibility planning, for environmental and health concerns, the challenges related to its implementation should be resolved to indeed supporting urban planning practices and improving public transport competitiveness versus car use.

In order to assess how developments of land use and transport systems affect public transport competitiveness versus the private cars, it is useful to identify planning support tools, more specifically, accessibility instruments that are relevant for planning and development of land use and transport systems that contribute to reduce transport demand and to shift mobility towards less car use by increasing public transport competitiveness. Moreover, as these developments are to a large extent in public authorities' hands, simple and user-friendly indicators need to be identified to tackle planning practitioners' needs on improving public transport (and bicycling and walking) competitiveness versus the private car in opposite to the lack of goal achievement that can be found in current European plans.

This report is organised as follows: First, we discuss accessibility concepts, components and approaches. Then, we present a the most basic accessibility measures and their role in reveal the relative competitiveness of public transport versus the car. Subsequently, we provide an overview of relevant accessibility instruments as planning supporting tools, especially those with a comparative approach between two modes of transport. In the last section, we present a proposal of accessibility indicators based on the basic measures able to easily reveal the relative competitiveness of public transport versus the car.

3. Accessibility measures, components and approaches

Accessibility measures provide a useful framework to support transport planning decisions for the design of integrated land use and transport policies (Silva & Pinho, 2010). These measures combine several indicators around a specific goal to orient and support planning practitioners' decisions. Among the specialised literature, several accessibility measures are available with different purposes, components and approaches, depending on the aim such measures are designed to overcome. This multifaceted aspect of accessibility contributes to the emergence of different ways to the designing of such measures, being difficult to choose only one considered "right".

To measure one must first recognise that the measurement of accessibility holds up to 4 components : transport, land use, temporal and individual (Geurs & van Wee, 2004; Geurs & van Eck, 2001). Accessibility measures are developed by combining these four interdependent aspects into different types of measures in different levels of complexity. The transport component represents the resistance or impedance factor measured by travel time and cost, expressing the disutility by mode depending on the demand and supply of the transport system (Silva C. , 2018). The land use component measures the distribution of potential destinations, magnitude, quality and character of the activities, expressing the motivational or attractional factor relying on the offer of activities. The other two components consist of the temporal component that reveals the availability of the activities at different times during the day/week, and the individual component which reflects personal preferences or (physical and economics) capabilities to access these activities (Geurs & van Wee, 2004; Geurs & van Eck, 2001).

Although the knowledge that the incorporation of all these aspects (Figure 1) resulting in increased complexity in planning support instruments (Geurs & van Wee, 2004), and thus reduces the likability to use them by planning practitioners, it is important to understand the implications of excluding one or more components to measure accessibility (Silva C. , 2018). The land use and transport components are seen as the external conditions to spatial structure attract or constraint access to activities (Silva & Pinho, 2010) while the temporal and individual elements express the circumstances that may influence the chosen opportunities (Geurs & van Wee, 2004). Both land use and transport are simple to understand by the demand and supply concepts allowed by the urban structure. The land use component can be measured by location and number of opportunities, while transport component usually is measure by time, distance or cost according to the considered mode (e.g. transit and car). Recently, authors also start to use CO_2 emissions as the impedance (or cost) factor (further information Kinigadner et al. 2019).
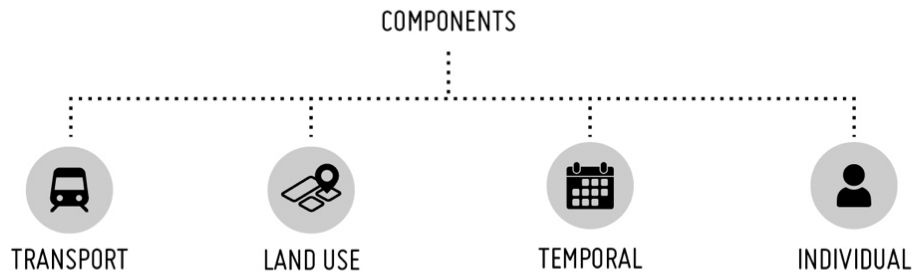
Figure 1 – The four components of accessibility measures.
Based on Geurs & van Eck (2001) and Geurs & van Wee, (2004)

The following step to operationalise a measure of accessibility is to define the approach the measure will be developed. As well as the incorporation of components implies different levels of complexity, accessibility measures might assume different types of approaches regarding the aim or planning goals they are supposed to overcome.

As mentioned before, the specialised literature categorises the accessibility measures in different ways, and therefore, it is not possible to take only one approach as correct. A very common approach is the one suggested by Geurs and van Eck (2004), which is based on three main perspectives:

i) Infrastructure-based accessibility measures: includes the analysis of the infrastructure's performance (e.g. average speed; average road network; level of congestion) but do not include land use component;

ii) Activity-based accessibility measures: analyse the range of the available activities and opportunities with respect to their distribution in the space. These can be divided into geographical (e.g. jobs accessibility) and time-space measures (analyse accessibility at micro-level and include '*the activities in which a person can participate at a certain time)*;

iii) Utility-based accessibility measures: are usually used to analyse the individuals' benefits derive from the land-use transport system (economic studies).

Derived from activity-based measures, the location-based accessibility measures are the most commonly used in planning practice, comprising mostly of the land use (where activities are distributed) and transport (the mean allowing access to activities) components, which may be often combined with other components revealing temporal and individual aspects. Also derived by the activity-based measures, person-based accessibility measure assesses accessibility for a

group of individuals according to their socioeconomic characteristics (e.g. income, age, educational level).

The following Table 1 is inspired by Geurs and Van Eck (2004) work and summarises accessibility measures' types (or approaches) considering the four components. There are several possible approaches to measure accessibility according to the inclusion or exclusion of one or more components, which generally depends on the planning goal such measure is designed to. For instance, activity-based measures can consider only transport and land use components to assess the accessibility to certain activities within a certain time and transport mode, regardless of the temporal and individual constraints.

Table 1 - Types of measures and components of accessibility. Adapted from Geurs & Van Eck (2001).

Types of measures	Transport	Land Use	Temporal	Individual
Infrastructure-based	travel speed; vehicle-hours lost in congestion	-	peak-hour period; 24-h period	trip-based stratification, e.g. home-to-work, business
Activity-based	travel time/cost between locations (by mode)	amount and spatial distribution of the opportunities	temporal constraints or availability of activities in periods of day/week	target group (students) for specific type of activities, (school)
Location-based	travel time/costs between locations of activities	amount and spatial distribution of the demand for and/or supply of opportunities	travel time /costs may differ between hours of the day, between days of the week, or seasons	stratification of the population (e.g. by income, educational level)
Person-based	travel time/cost between locations of activities	amount and spatial distribution of supplied opportunities	temporal constraints for activities and time available for activities	accessibility is analysed at individual level
Utility-based	travel costs between locations of activities	amount and spatial distribution of supplied opportunities	travel time and costs may differ between hours of the day, between days of the week, or seasons	utility is derived at the individual or homogeneous population group level

Among accessibility instruments, two main goals characterize the usability of the tools, one of them supports land use developments (where to locate residences, activities and services), while the other focus on managing and encouraging or reduce the use of specific transport modes. Instruments can tackle one of these goals or both (multi-disciplinary) (Bertolini, Hull, Papa, Silva, & Ruiz, 2019). Generally, the design of accessibility instruments uses not only one, but many

of accessibility indicators, derived from a combination of types of measures to orient the accomplishment of one or several planning goals.

As urban planning is essentially suitable according to each city's context, the designing of accessibility measures may be also scale-dependent of the location the measure is being developed for. For example, a specific mode can be chosen to perform opportunities' accessibility for a municipal level, but it might be inappropriate to perform peoples' accessibility at small scales. Most of the studies on regional or municipal scale analyse accessibility by the car and (or) public transport perspectives, while local accessibility studies commonly assess active or non-motorised (e.g. walking and cycling) accessibility.

The purpose of travel or type of opportunities also might vary according to scale of analysis. For example, the access of jobs opportunities' it is likely to be represented at the municipal (or regional) level so the results better reveal whether opportunities are equally distributed to people, according to their available mobility choices. On the other hand, if the assessment is focused on a local or neighbourhood scale, other types of opportunities might be considered, such as activities related to daily needs (e.g. primary school, food facilities, health and recreational). Small scales also require smaller spatial datasets and refinement on the transport component data in order to measure accessibility at the pedestrian perspective.

In the present work, we focus on the measures designed for a municipal (or regional) scale, which may be easily included in the decision-making processes as a supporting planning tool in medium-sized municipalities. Our objective is increasing the knowledge on accessibility measures that aims to compare the performance between public transport and the private car to reveal their relative competitiveness. The following section provides an overview of relevant accessibility instruments as PSS, especially those with a comparative approach, presenting the role of such tools in support planning goals as the shifting mobility towards less car use through improving public transport competitiveness.

4. Basic Accessibility Measures

The literature shows a variety of accessibility measures with different planning purposes and levels of complexity. In Bertolini et al. (2005) understanding, to be useful for planning purposes the accessibility measure should meet two basic requirements, with respect the use and perception of people in a certain area and must be easily understood to practitioners that taking part in the planning processes.

In this section, we explore the most basic types of measures for practical implementation and framed around the way that people make their mode choice decisions, particularly between private car and public transport. According to Silva (2018), we divide the basic measures of accessibility in Distance (or time), Isochrone, Contour (or Cumulative Opportunities) and Potential (and Gravity) measures. The concept will be explored for each basic measure, in addition to the possible spatial representations (maps) of accessibility that can be built from the measure.

4.1. Distance (or Time)

Figure 2 - Conceptual scheme comparing different transport modes travel times and/or distances.

The easiest accessibility measure is the Distance (or Time) measure. It estimates the *degree to which two places or people are connected* (Geurs & van Wee, 2004), considering the most favourable route network expressed by travel times or distance (Silva C. , 2018). This measure can be used as standards for the maximum travel time distance to given two points, A and B, where A and B represent an origin and destination location (or transport infrastructure) (Geurs & van Wee, 2004). The distance-time to overcome them can be measured in a simple straight line (Euclidean distance) or taking in account the street network to a more accurate assessment of the distance/time from two locations.

A practical example of this type of measure is to provide a map that represents the time (or other impedance factors as distance and/or cost) spent to access certain activity considering each transport mode separately. The distance-time measure is commonly used as one of the UK

planning system indicators to measure access to key services (or activities) in British municipalities (Department for Transport, 2014). Derived from data from the National Travel Survey, users' travel times are measured for eight types of service considering the transport modes (public transport/walking, car and bicycle). Table 2 presents the eight key services and respective lower and upper travel times. The lower time is based on the average time of all trips and the upper time is the "end of journey times" by more than 80% of users (Department for Transport, 2014)

Table 2 - Accessibility to key services. Based on Department for Transport (2014).

Activity/ Service	Lower Time (min)	Upper Time (min)
Employment	20	40
Primary Schools	15	30
Secondary School	20	40
Further Education	30	60
Health Centres	15	30
Hospitals	30	60
Food Store	15	30
Town Centre	15	30

By combining several maps of different service or activity accessibility by mode, it is possible to identify which transport mode might be more attractive (or more competitive) than others comparing their travel times (seen as a cost in individuals' perspective) inducing or constraint travel choices.

To increase the richness of data using a Distance/Time measure it is possible to combine information using, for example, a population density map resulting in a composite map with information of populated areas served by an activity (e.g. school) in a given distance-time separation by mode (e.g. 15min walking or 10min driving). In planning practice, this map can be useful to identify areas in the city or the (groups of) people that is more or less served by certain activities, according to the transport mode time travel. Combined with other maps, it may provide an analysis of different types of activities accessed by different transport modes revealing the potential mobility the spatial infrastructure provides (Silva C. , 2018). A comparative approach using simple Distance/Time measure easily provides information of urban inequalities that can be useful to analyse the competitiveness between two transport modes as the private car and public transport.
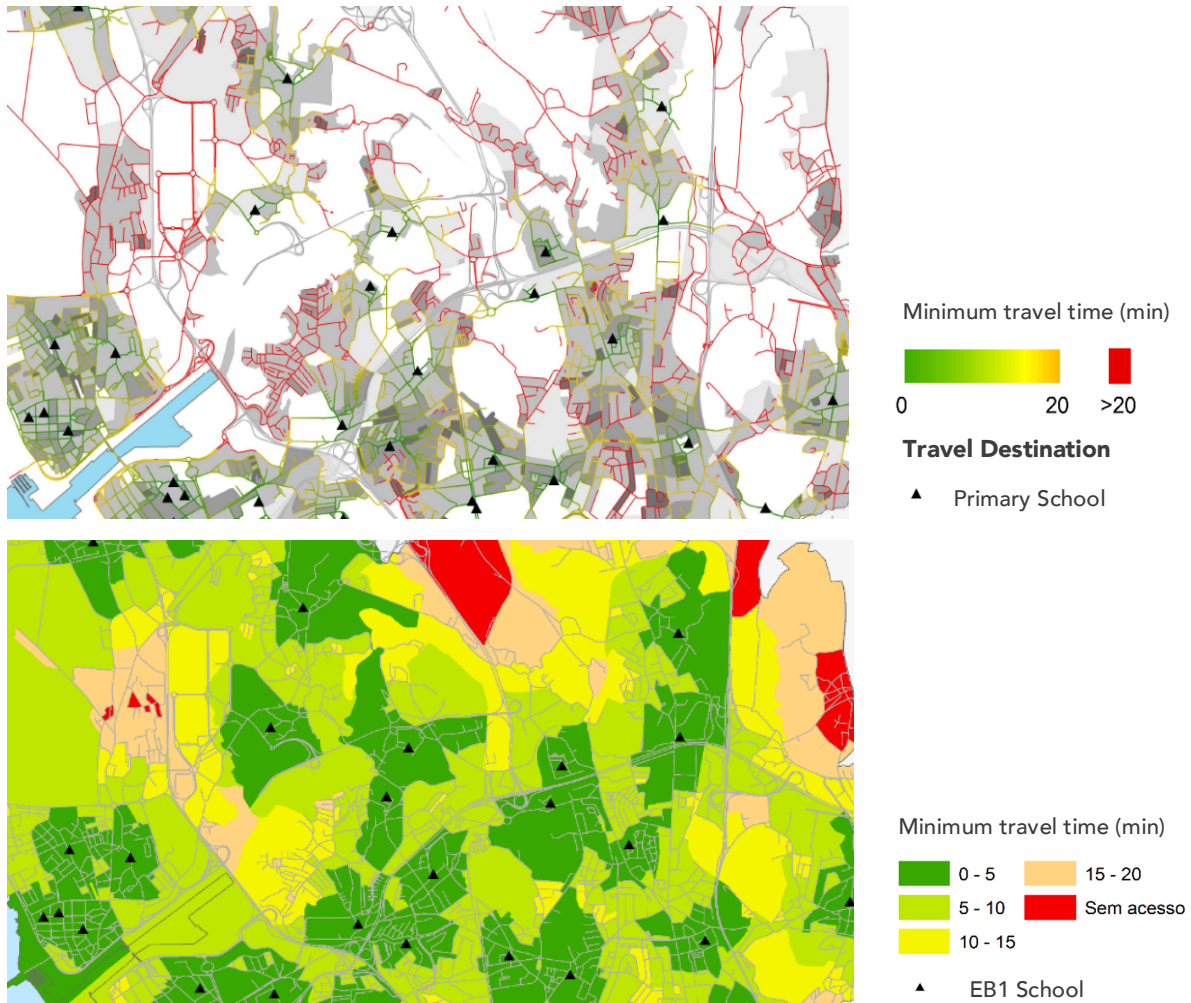
Figure 3 - Examples of maps using Distance/Time measure to assesses accessibility to primary schools in Matosinhos, Portugal. Source: Pinho et al. (2016).

Figure 3 presents two examples applying a Distance/Time measure to assess accessibility to primary schools by walking. The first map (above), the measure is represented along with the network by a colour scale overlapping the population density map at the census tract level; the second (below) the measure is not represented in the network but in each subsection and no information on population density is given. Another difference between these two maps is that in the first example, the red colour represents parts of the network with access to schools in more than 20 minutes walking while, in the second example, the red colour represents the subsections without access to primary schools in the same travel time and mode.

4.2. Isochrones (one destination)

We also can measure accessibility using an isochrone reference. The spatial representation of this measure is an equidistance line of areas with or without access from certain origin location, transport modes or both (Silva C. , 2018). This line of equidistance (in metres or time) as the Distance/Time measure, can be measured by Euclidian distances or considering the network infrastructure to a more accurate assessment. From a given point (which might represent e.g. an activity), the Isochrones shows the areas with accessibility by a specific mode within a fixed travel time, assuming that point as a desirable destination.

There are various possible applications for this measure. An example is mapping an activity type or transport infrastructure (e.g. bus stop) and calculating the area from/to which people can access them within a limit of time (e.g. 15-minute walking). Combining it with a population density map, the isochrones might reveal where the transport infrastructure is meeting the demand and where is not. Spatial inequalities in the urban territory can also be identified using Isochrones measures, for example, revealing the activities without accessibility (or accessible by specific transport mode) in a given time travel distance.

Similar to the Distance/Time measure, as many data layers are combined (such as population or job density), increased will be the analysis detail useful to support planning decisions. The main difference between Distance/Time and Isochrone measures is that while the representation of the first reveals the distance or time in the degree of proximity, the last consider a limit time within which all opportunities have access to, and which above this limit have no accessibility at all. Also, while the Distance/Time measure considers the closest way from one location to another, Isochrones considers all possibilities inside the covered accessible area.

In the following Figure 4 uses the same example of primary schools, from which Isochrones of 10-minute walking are applied using both Euclidean (above) and network infrastructure (below) parameters. Overlapped to the population density map, these two maps provide easy-to-read information whether the schools are located in an area with more or less population, as well as reveal more populated areas without access to schools for this mode and travel time considered. Another insight these maps provides is that if there is no available school by proximity, people are likely to travel using another transport mode (e.g. car) to access further school options.

Accessible Area

☐ 10-minute walking

Travel Destination

▲ Primary School

Population Density (inhabit./km2)

1 - 1000	5 001 - 10 000
1 001 - 2 000	> 10 000
2 001 - 5 000	
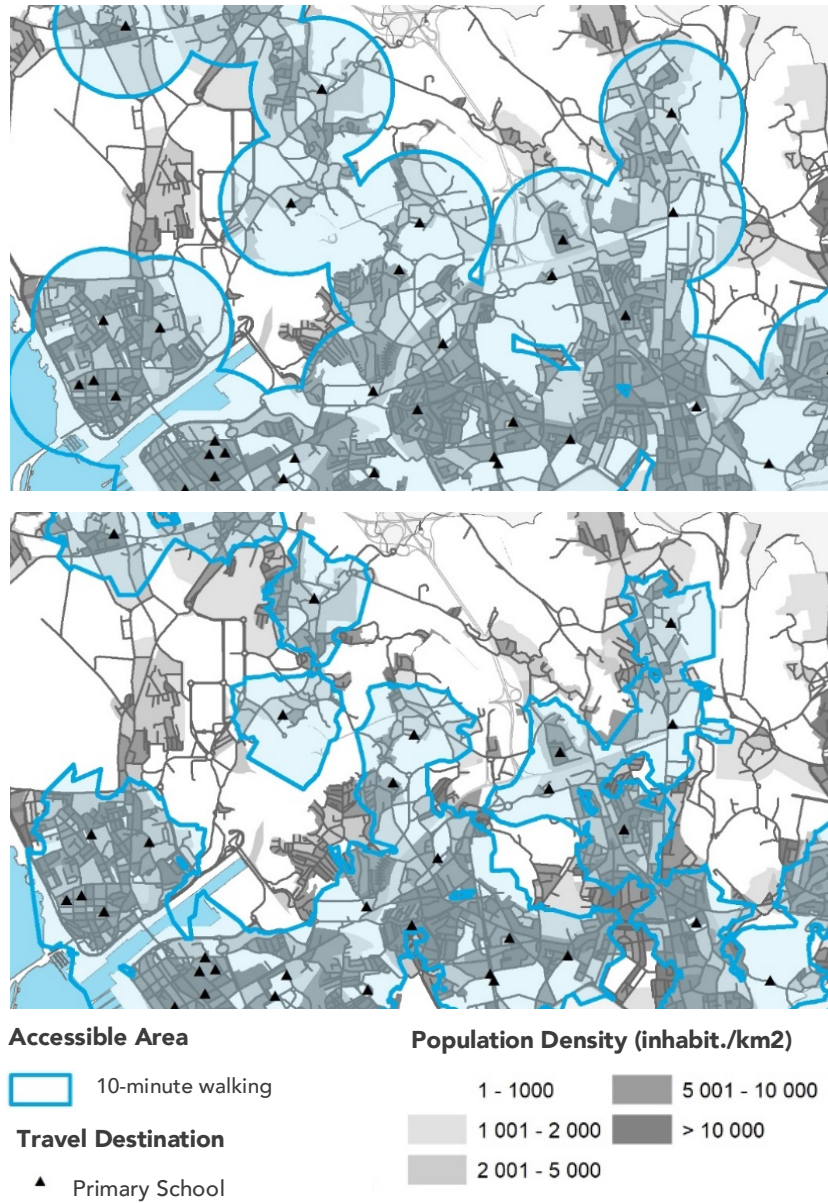
Figure 4 - Examples using Isochrone measure – using Euclidean (above) and network parameters (below) - to assess accessibility to primary schools in Matosinhos, Portugal. Source: Pinho et al. (2016).

4.3. Contour measure (or Cumulative opportunities)

The contour measure uses the isochrone measure and adds the account of the number of opportunities. This measure is also known as Cumulative Opportunities, Proximity Count or Daily Accessibility, and it counts the number of reachable activities within a given fixed travel time, distance or cost (Geurs & van Wee, 2004). Derived from the Isochrones, the spatial

representation of this measure considers not only one origin location but several reachable activities within a fixed distance, time or cost. Also, when fixed opportunities accounted, the contour measure has the potential to assess the time or cost (average or total) required to access them. The contour measure might be based on the origin – measuring the number of activities available within the accessible area -, or considering the destination locations – accounting for the number or percentage of population that can access such activities.

Many authors do not differentiate Isochrones and Contour measures since consider the last derived from the first, but a clear distinction between the two measures, presented by Silva (2018), seems important for a better understanding and might be helpful in the acceptance of such measures by planning practitioners. Whilst Isochrone measure allows for direct and visual communication on the results, the Contour measure expresses a mathematical equation (e.g. ratios, sums) which require a minimum degree of interpretation of the results.

Distance/Time, Isochrone, Contour measures are easy tools to operationalise, to interpret and to communicate, considered important advantages in planning practice (Silva C. , 2018; Geurs & van Wee, 2004). However, some limitations highlighted by Geurs and van Wee (2004) concerning theoretical criteria. First, Distance and Contour measures combine transport and land use accessibility components, but do not evaluate their combined effect. Also, these basic measures do not take into account the distance decay nor competition effects regardless of the demand distribution for an opportunity and capacity limitations of several activities (e.g. the number of students in schools or the number of beds in hospitals). Finally, Distance/Time and Contour measures perform arbitrary issues treating all opportunities equally desirable as a result of excluding temporal and individual components.

Figure 5 presents again the primary schools' example applying a Contour measure. From an isochrone of 10-minute walking considering the central point of each spatial unity (centroid) as the origin location, it counts the number of primary schools within the accessible area. Contrary to the "direct" visual representation given by the isochrones in the previous example, here the result is disaggregated at the level of the census tract, where instead of representing the population density, it shows the number of schools accessible from each of the subsections in this mode and time considered. The derivations of this map are numerous. For instance, we can combine the population density data with the number of accessible activities by ratios, or calculate the accessibility only for the "target group" for that activity (e.g. students).

Figure 5 - Example of application of Contour measures, expressing the number of primary schools accessible in 10-minute walking from all origin locations (centroids) of Matosinhos, Portugal. Source: Castro, N. (2020).

Applying the same measure from the same origin locations (centroids), we can also count the number of people who lives within the accessible area and who has access, in this case, to at least one school less than 10min away from home (Table 3). Other types of activities and services can be measured with the same parameters.

Table 3 - Average population with access to primary schools in 10 min. walking.

	Population	% Population
Walking	117 808	67%
Total Population	175 452	

4.4. Potential (and Gravity) measure

Potential measures have emerged in accessibility literature aiming to overcome some of the limitations presented in the previous subsection (Geurs & van Wee, 2004). This measure counts the number of activities within the accessible area but considers the relevance of opportunities increases or decreases depending on the distance from the origin location (Silva C. , 2018). This measure of accessibility is based on the measure of cumulative opportunities, also using the count of opportunities found in the area of accessibility. However, instead of resorting to distances or time limits for accessibility areas (isochrones), it considers a distance decay function. Hence, more distant activities might have less influence on accessibility than closer activities.

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The formula for this type of measure is:

$$A_i = \sum_j O_j \, f(d_{ij})$$

Where, A_i - Origin Accessibility; O_j - Destination Opportunities; $f(d_{ij})$ - Decay function; d_{ij} - Distance, time or cost from i origin and j destination.

Similar to the Contour measure, the Potential measure can be based on origin or destination activities' locations. In Potential measures, the limit of the area with or without accessibility (represented by Isochrones in Contour measure) is replaced by a residual weight of the opportunities depending on the proximity. Thus, while the Contour measure consider all opportunities equally important within a limit of time/distance or cost, the Potential measure gives a weight to opportunities proportional to the distance or the size of the activity.

The potential measure is often found in the literature as Gravity measure since several authors treat them as the same type of measure. Despite the subtle difference, it is important a clear distinction between the two for a better understanding of such measures avoiding theoretical misinterpretations. Both Potential and Gravity measures consist in count the number of opportunities within a given distance/time or cost to access them, applying different weights to different opportunities. In Potential measures, the weight depends on the proximity of the opportunities, being a distant activity seen as less relevant from a given origin location. In Gravity measures, in addition to the distance decay is applied a weight that refers to the size or capacity of such opportunities.

The distance decay and competition effect are some additional operational details aimed to overcome shortcomings from simple Distance/Time, Isochrone and Contour measures. More additional details might include other temporal or individual constraints bringing more accuracy to Potential and Gravity measures but also increasing the complexity to operationalise the tool, interpretation of data and communication of the results in planning practice.

To summarize what have been said so far, the literature review revealed that the more included components and data into the models, the more complexity added on these tools, and therefore, more specific knowledge needed to operationalise accessibility instruments. Although the complexity allows overcome many theoretical shortcomings of simplistic measures, it might have been contributing to moving practitioners and policy-makers away from adopting accessibility measures.

Figure 6 resumes the potential of basic accessibility measures in planning practice, regarding the (1) different components taken into accounts, (2) the easiness in operationalising, communicate and interpretation, and (3) the potential users based on the knowledge required to run accessibility measures in planning practice.
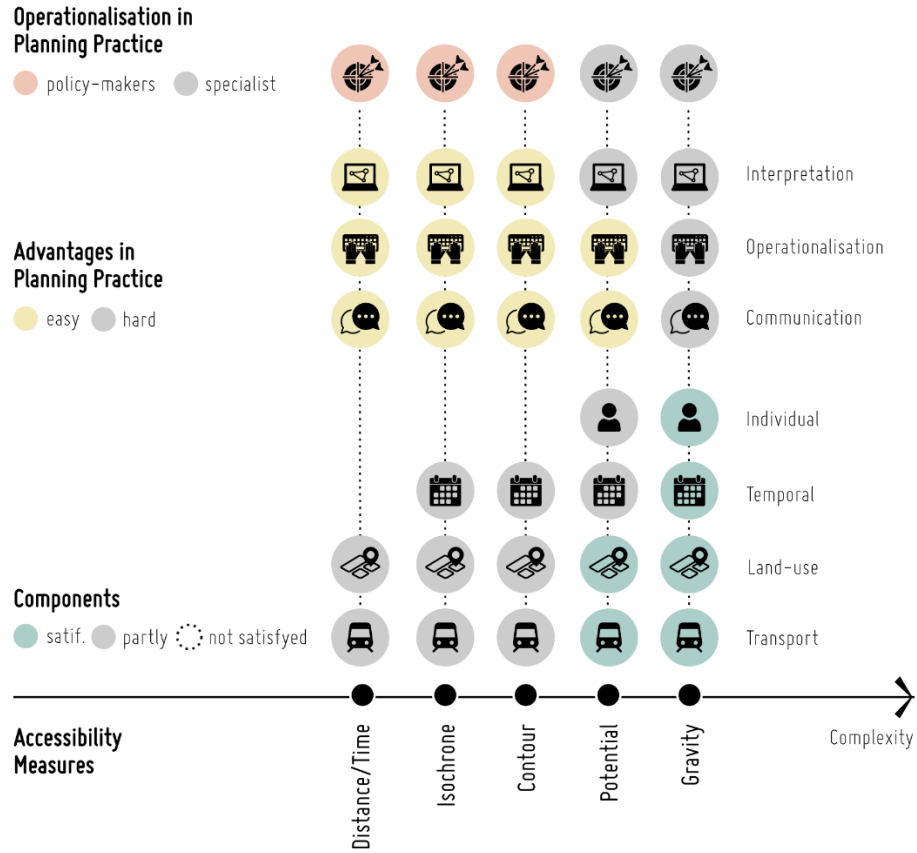

Figure 6 - Type of measures in different scales of complexity in planning practice.
Based on Geurs and Wee (2004).

5. Accessibility Instruments (PT vs Car)

The following instruments were found among a wide range of accessibility tools but only those that are open source, easy to use and that also present a potential way of measuring comparative accessibility between private car and public transport are discussed here. A recent and more extensive review on European accessibility instruments can be found in Bertolini et al. (2019).

The Table 4 summarizes the instruments presented in this literature review, classified according to their potential to provide a comparative analysis across modes namely PT and car. Some of these instruments were specifically designed to measure the relative accessibility between PT and car (SAL, Urban Access); others were developed for other planning objectives but having accessibility measures for PT and car, allow comparative analysis (ACCALC, German Approach); other instruments are developed specifically to measure PT accessibility but don't allow comparison across modes.

Table 4 - Accessibility instruments for PT and car analysis.

Tool	Designed for comparative analysis	Can be used to comparative analysis	Designed only for TP accessibility
SAL	x	-	-
LUPTAI	-	-	x
SNAMUTS	-	-	x
ACCALC	-	x	-
Connectivity Toolkit	-	x	-
Urban Access	x	-	-
Spatiotemporal Accessibility	x	-	-
Erreichbarkeitsatlas	-	x	-
GraBAM	-	-	x

The instruments are detailed in the following Table 5 providing an index of analysed accessibility instruments and respective indicators used in such accessibility tools. This index may offer insights for a comparative assessment of the public transport and private car regarding the competitiveness between modes. Each instrument is then discussed in the next subsections.

Table 5 - Index of accessibility instruments.

Tool	Author	Type of Indicators	Indicators	Description
SAL	Silva & Pinho 2010	Contour measure	DivAct	Measures the number of accessible activities type for each transport mode
		Comparative Analysis	Comparative Accessibility Measure	Classifies areas according to 9 clusters of accessibility as a result of the combination of accessibility levels across all modes considered
LUPTAI	Pitot et al. 2006 Queensland Transport	Activity-based measure	Accessibility analysis to 5 categories by walking	Measures accessibility to a key destination using walking distances specific for each destination according to 4 different intervals defined for each accessibility level
			Accessibility analysis to 5 categories by public transport	Same as before but for public transport
		Aggregated measure	Combined accessibility measure by walking and Public transport	The two previous values are then merged together to form accessibility levels of the land parcels to selected land-use destinations
SNAMUTS	Curtis & Scheurer 2016	Infrastructural-based measure	Closeness	measures the ease of movement along the PT network by speed and frequency
		Network measure	Degree Centrality	measures the directness of the journey by counting the number of transfers between each pair of activity node
		Contour measure	Contour Catchments	measures the number of residents and jobs within the walkable catchment areas of activity nodes that can be reached within 30 min PT travel time from the original node
		Infrastructural-based measure	Speed Comparison	measures the competitiveness of PT against the car by a ratio between travel time for each car and PT for the route between each pair of activity nodes
		Network measure	Betweenness centrality	measures the density of "travel opportunities" generated by the PT network or "movement energy"; nodal connectivity (measures the level of inter modality of each activity node
		Aggregated measure	Composite Indicator	compiles the above indicators into a scaled map from 0 to 10
British Accessibility Statistics (ACCALC)	Department for Transport UK	Infrastructural-based measure	Travel Time	Average shortest time to reach nearest destination
		Activity-based measure	Destination	% of population that can access a service within a certain time
		Contour measure	Origin	Number of services available within a certain time

Connectivity toolkit	Transport for London	Contour measure	PTAL Public Transport Access Level	Classifies areas of the city according to the easiness to reach transport facilities
		Infrastructural-based measure	TIM Time mapping	Calculates the travel time between areas of the cities
		Infrastructural-based measure	CAPITAL Calculator of Public Transport Access in London	Calculates travel time from a certain origin to all other destinations
			ATOS Access to Opportunities and Services	Classifies areas according to the amount of time needed to reach essential services
		Gravity-based measure	Catchment Analysis	Calculates Coverage areas for any origin or destination defined. It can also include socioeconomic data.
Urban Access	Benenson et. Al., 2011	Infrastructural-based measure	Access Area	Ratio of the travel time between bus/car to certain origin locations
			Service Area	Ratio of the travel time between bus/car to certain destination locations

5.1. SAL

An interesting approach to a comparative analysis can be found in the Structural Accessibility Layer (SAL) (Silva & Pinho, 2010). The SAL is an accessibility-based tool that geographically represents the levels of accessibility by mode of transport (non-motorised, car and public transport) to different types of services or opportunities, in a comparative way.

The SAL includes two main measures, the *DivAct* (diversity of activity index) and the comparative accessibility measure that are assessed at a high spatial disaggregation level. The first is a contour measure and it counts the number of activity types from a given origin. The *DivAct* can be scored for each transport mode from 0 (no accessible activities) to 1 (all activities are accessible). The comparative accessibility measure uses the outcome of the *DivAct* to develop a comparative analysis of the accessibility across all transport modes considered.

The comparative accessibility measure consists of 7 clusters of accessibility that combine areas providing high accessibility levels by the same transport modes. For instance, cluster III means that an area offers favourable conditions to the use of all modes due to its high accessibility to a range of activities by any mode whereas class VII does only favourable high accessibility levels by the car and thus only offers conditions for car use.

5.2. LUPTAI

LUPTAI (Land use and Public Transport Accessibility index) is an Australian method useful for evaluating people accessibility to important destinations by exclusively public transport and walking (health, education, retail, banking and employment) that can be calculated trough an ArcGIS add-on. Despite developed for public transport accessibility analysis, may offer some insights for this review.

This tool produces a map that highlights areas of the city of No, Poor, Low, Medium and High accessibility. The output can be weighted with population density.

The methodology relies on destination-based accessibility analysis that produces a composite of index of measures (accessibility analysis to each destination type) that is aimed at presenting the levels of interaction between land use development and transport supply according to its level of accessibility. The accessibility analysis to each one of the destinations considered produces "values measures" that consist of travel distance or time between two locations via the transport network. To each destination considered a scale of accessibility according to distance and travel time was defined that gives a classification of the land parcels accessibility levels for walking and PT. A combination of both results in the composite index for all destinations, based on a weighting system. The final visual representation can also be weighted to the population density (Pitot, Yigitcanlar, Sipe, & Evans, 2005).

5.3. SNAMUTS

The Spatial Network Analysis for Multimodal Urban Transport Systems (SNAMUTS) is another Australian GIS-based accessibility instrument that calculates eight accessibility metrics for any pair of activity nodes[1] with the provided frequency of public transport in the inter-peak time. As LUPTAI measure, SNALUTS measure was developed for public transport accessibility analysis only, but its indicators may give some insights as well.

The indicators of SNAMUTS are: Closeness (measures the ease of movement along the PT network by speed and frequency); Degree Centrality (measures the directness of the journey by counting the number of transfer between each pair of activity node); Contour Catchments (measures the number of residents and jobs within the walkable catchment areas of activity nodes that can be reached within 30 min PT travel time from the original node); Speed Comparison

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[1] Activity nodes are activity centres across a metropolitan area that in the Australian case are defined in planning documents.

(measures the competitiveness of PT against the car by a ratio between travel time for each car and PT for the route between each pair of activity nodes); Betweenness centrality (measures the density of "travel opportunities" generated by the PT network or "movement energy"; nodal connectivity (measures the level of inter modality of each activity node); finally, a Composite Indicator compiles the above indicators into a scaled map from 0 to 10. Further measures can be also obtained from the indicators above, one is the network coverage that uses the contour measure values for all activity nodes overlaying it with population and jobs contained within the catchment area (Curtis & Scheurer, Planning for sustainable accessibility: Developing tools to aid discussion and decision-making, 2010).

5.4. ACCALC

ACCALC is a similar instrument operated by the British Department for Transport and firstly sketched by Halden (2002) (Department for Transport, 2014).

The ACCALC indicators measure the access to eight key services: employment centres, primary schools, secondary schools, "further education institutions", health centres (family doctor), hospitals, food shops and town centres. There are three types of indicators: *travel time indicators, destination indicators and origin indicators.*

The first measures travel time needed to reach the nearest service and can be calculated by any mode of transport (public transport, walking, car and cycling). An example of this application is their annual statistics of average travel time across the 8 services by each of the transports considered. The destination indicator measures the 'coverage' population of a service within a certain time, it can also look for particular social groups at risk or exclusion, it measures for instance the percentage of the population able to access each service within 15 min across all the modes considered. The last indicator measures the number of services available within a particular area (i.e. LSOA: lower layer output areas or the smaller statistic area) according to selected journey times and mode of transport, for instance, the number of services available within 15 minutes by PT, bicycle or car.

The time thresholds for each of the eight services are based on the median travel time for each of them derived from their National Travel Survey data. Data used for the calculations include number of jobs per LSOA, location of schools, health centres, hospital, food shops, town centres and socioeconomic data. By requiring assessment of accessibility levels by 4 transport modes (including car and public transport) this framework allows for comparisons between car and public transport competitiveness.

5.5. Connectivity Toolkit

Still on British territory, a complex tool, the Connectivity Toolkit by Transport for London (Assessing transport connectivity in London, 2015) contains a range of indicators used to assess accessibility in London that are presented in an interactive webpage, the WebCAT. The toolkit comprises the PTAL measure (Public transport access level) that rates areas of the city according to its proximity to public transport and its level of service; a set of Travel time mapping measures, that assess time travel from selected origins/ destinations or the length of travel according to a given time; and the Catchment measure, that evaluates how many types of services are reachable from a certain travel time and location.

The PTAL measure is exclusively used for public transport and spatially represents how well a place is connected to public transport services in a scale of 9 categories (0,1a, 1b, 2, 3, 4, 5, 6a, 6b). A higher PTAL means the location is at a short walking distance to the nearest PT stop, the waiting times are short, there are more services nearby, there is a major rail station nearby or any of the combinations above. The data needed for calculating the PTAL includes a list of desired origins (houses, offices, shops, etc.), the location of public transport stops and stations, walking network, public transport routes and frequencies for current situations or future scenario. The PTAL can be used in strategic studies as a key determinant of desired housing density in different parts of London, those areas where there is a higher density of the public transport network are more suitable for intense development. It can be also used as determinant of how much parking should be provided in residential areas, in a sense that less parking should exist in places with good PT (Transport for London, 2015).

Among the Travel Time Mapping analysis developed by TfL, the TIM (travel time mapping) estimates the routes to go from one zone of the city to another, either by car or by public transport. As zones are small areas of the city that can be either origins or destinations to another zone, there are many possible origin-destinations pairs. The TIM is useful for identifying existing areas that need transport improvements as well as improvements needed for new developments. A similar and complementary tool, the CAPITAL (Calculator of Public Transport Access in London), despite of the name, is also useful for mapping travel times by car. It is a more complex model than TIM as instead of calculating zone pairs, it shows how long it takes form a selected origin (a town centre, a station or a development site) to all other destinations in a more local and detailed scale and, it also takes into account time to access the transport network. Complementary to the CAPITAL measure, the ATOS (Access to opportunities and services) indicates the easiness to access essential services and employment by PT or by foot. It uses a score from A to E, where A means higher accessibility to more opportunities. The ATOS identifies the 10 nearest destinations of each service considered (employment, educational institutions,

hospitals, supermarkets and public open space) and from that the time travel by public transport obtained from CAPITAL values is obtained. Based on that, the nearest destination for each type of service or three nearest (for health and education) are selected, then an average travel time and a standard deviation of travel times for type of service is calculated. The score is given according to the travel time from the origin to the nearest destination compared with the average travel time for all locations. Despite of the promising results, the ATOS measure is mainly useful for identifying areas that are denser than other, in term of close by activities because of the difficult to create a meaningful combination of scores (Transport for London, 2015).

The Catchment final measure of the London connectivity toolkit (Transport for London, 2015) analyses all destinations that are easy to reach from a specific origin. In other words, it can measure the catchment area of a service (a shop, school or hospital) in terms of population, or catchment of a residential are being employment availability. Most of their analyses use a maximum travel time of 45 minutes or sometimes 60 minutes by one or different modes of transport. The catchment area can present socio-economic information, number of services available or the different travel times within the same catchment area. Different analyses can be performed using the catchment area measure, such as analyses on the additional jobs within a certain time driving or by public transport if a new infrastructure or route is implemented, or the catchment of active population in the same case, or the number of jobs available within 45 minutes, or the catchment of town centres/ universities (or specific locations as new developments/ services, etc.) by different modes of transport within 45 minutes. These analyses are simple and useful for identifying areas that need better transport service, or to analyse how areas may change if new infrastructure is implemented or where to locate new businesses or services.

5.6. Urban Access

The Urban.Access (Benenson, Martens, Rofé, & Kwartler, 2011) is a non-European ArcGIS extension developed to estimate car-based and transit-based accessibility to employment and other land uses developed in the middle east. It consists of a direct comparison analysis between car and public transport, useful for planning for reducing car dependence as well as for creating more equitable transport system.

The Urban.Access is a 'location-based measure' of accessibility to urban activities and employment that estimates travel time between origin and destination for bus and car. Both consider the necessary walking time or transfers and waiting time for the bus case. An access area of all reachable destinations is obtained from a given origin, transport mode and travel time.

The same is done for origins, a service area of all possible origins is obtained from a given destination by transport mode and travel time.

Two comparative measures obtained from ratios of access area bus/car and service area bus/car reveal the gaps between transit-based and car-based accessibility. For instance, a Bus/Car service area ration can be the sum of coverages for a certain origin (e.g. number of apartments in low income neighbourhoods) that can be accessed for a specific time by b7us and by car.

5.7. Spatiotemporal Accessibility

In Fransen et al. (2015), public transport accessibility is compared to the access by car at regular time intervals for the Flanders area of Belgium. They present a spatiotemporal accessibility measure that calculates the optimal path for each transportation mode at specific times of the day used for further comparison between public and private transport trough a ratio. The calculation involves origin-destination cost matrices (within a maximum travel time of 60min) between centroids then calculated the number of jobs for each area. The ratio is defined by the number of jobs accessible through PT x Car. The ratio highlights areas with insufficient PT (poverty line = 0.05%, meaning that inhabitants that are not able to reach a number of jobs equal to or higher than 0.05 of jobs accessible by car are defined as access impoverished).

5.8. Erreichbarkeitsatlas

Anotherwas developed for the European Metropolitan Region of Munich (EMM), to support regional planning. The tool consists of a collection of measures of accessibility that have been developed over time and relies on isochrones and gravity-based measures for both private and public transport set up in a GIS toolbox. The measures include travel time to different locations of regional interest further classified within an index based upon the population and job potentials within reach of each municipality in the regional area. All of the accessibility analysis is based on structural (population and employment data) and transport supply data. Accessibility differences within a municipality are analysed by determining network-based catchment areas of points of interest (e.g. health-care, shopping, services, or public transport stations). An adaptation of the LUPTAI (Pitot et al., 2006) indicator is used to assess public transport accessibility based on its service quality and population density. This indicator uses public transport data and network data as input for a formula to calculate accessibility level by public transport for selected locations within a 20x20m grid. The locations are then classified within a five-categories-scale

using equal intervals. This classification is then overlaid by population density data to allow the visualization of areas with low density but high public transport accessibility or vice-versa, as means to improve either the transport service or urban development (Büttner, Keller, & Wulfhorst, Erreichbarkeitsatlas der Europäischen Metropolregion München (EMM), 2012; Wulfhorst, Büttner, & Ji, 2017; Büttner, Kinigadner, Ji, Wright, & Wulfhorst, 2018).

The formula to calculate the public transport accessibility indicator is:

$$\text{Accessibility}_{\text{Location}} = \sum_{k=1}^{n} Ck \times t_k \times v_k$$

Where "(n= Number of public transport stops that are reachable within a certain distance (2 km) from the current location; c = Closeness of the reachable stops to the current location – three classes of closeness are adopted (c= 6 if distance ≤ 0.5 km, c = 2 if distance ≤ 1 km and c = 1 if distance ≤ 2 km); t= Type of the reachable stops – an S-Bahn (suburban train) stop or non-S-Bahn stop (t = 3 for suburban train stops and t= 1 for non-suburban train stops and bus stops); v= Quality of the reachable stops (aggregated public transport service quality indicator, explained above); and k= The kth reachable stop." (Wulfhorst, Büttner, & Ji, 2017)

5.9. GraBAM

The GraBAM measures accessibility with gravity-based indicators of two types, the active accessibility (that measures the ease to reach activities within a zone) and the passive accessibility (that measures the potential users of a certain activity) calibrated by the travel cost. Those indicators can be calculated for a specific transport mode (road, rail or multimodal), for a certain trip purpose, for a destination category or specific social group. It is better applied to evaluate impacts of the implementation of new infrastructure or new transport services (Papa & Coppola, Gravity-Based Accessibility measures for Integrated Transport-land Use Planning (GraBAM), 2012). The GraBAM was developed only for public transport accessibility analysis, but as LUPTAI and SNAMUTS instruments, may offer some insight as well.

6. Using basic measures to reveal relative competitiveness

The knowledge presented along the previous sections concerning accessibility measures and instruments raises two important understandings. Firstly, there is a range of accessibility instruments developed to supporting planning decisions, including the assessment of competitiveness (or attractiveness) between two different transport modes as public transport and the car. However, the acceptability of such instruments, in practice, is still not widespread in addition to being often misunderstood among urban practitioners. Second, accessibility can be measured in different ways, for several purposes, at different scales, and for various transport modes (Silva C. , 2018; Geurs & van Wee, 2004) depending on the planning goals that the measure is supposed to overcome. In addition, as people travel from and to different locations, the activities can be measured considering their origin or destination locations (Silva C. , 2018; Geurs & van Wee, 2004).

Accordingly, in this section, we present a proposal of accessibility indicators which are considered easy to operate and interpret in planning practice particularly to assess the competitiveness between public transport and the private car. We illustrate how Time/Distance, Isochrones and Contour measures can be used to reveal relative competitiveness. The outputs of accessibility indicators are usually expressed in the form of maps, but often can be presented in percentages (e.g. representing the average population with access to certain activity by certain travel time by mode).

The following Table 6 presents examples of how Time/Distance, Isochrones and Contour accessibility measures can reveal the competitiveness between transport modes as public transport (PT) and the private car. Using GIS-based spatial representations, the intention is to understand how can we communicate the results with maps – side by side, overlapping or composite -, how can we use and interpret aggregated values; as well as some application examples.

Using a Time/Distance measure, the competitiveness can be expressed by using side-by-side maps of PT versus car accessibility, and also by using composite maps with aggregated values by ratio (PT/Car) or clusters. The second Isochrone measure we can also overlap two maps (PT+Car) providing an easy to read competitive spatial representation, in addition to present the results side-by-side or in composite values (in this case, the ratio is not possible). The third Contour measure express the data differently to the first measure (for instance, we measure accessibility both from origin and destination locations) but its communication to reveal competitiveness between modes is similar to the first measure: using side-by-side or composite maps of ratio and clusters of PT and car.

Table 6 - How the competitiveness between modes might be revealed using basic accessibility measures (maps).

Type of Measure	Maps			Aggregate Data	Application examples
	How the results are communicated with map(s)?			*How the results are communicated with aggregate value(s)?*	
	Side by side	*Overlapping*	*Composite*		
Distance/Time	PT vs. Car	-	PT + Car by Ratio or Clusters	Average time/distance a for study region	Silva et al. 2019; Pinho et al. (2016)
Isochrones	PT vs. Car	PT + Car	PT + Car by Clusters	-	(Benenson, Martens, Rofé, & Kwartler, 2011) (Kinigadner, Büttner, & Wulfhorst, 2019); Pinho et al. (2016)
Contour	PT vs. Car	-	PT + Car by Ratio or Clusters	Ex. Destination-based: Population accessible from school by PT and CAR; Ex. Origin-based: n° of schools accessible by PT and Car;	(Deboosere et al., 2018), Silva & Pinho, 2010; Pinho et al. (2016)

The next sections present illustrated examples of how the measures suggested in Table 6 can be used in concrete situations to reveal the relative competitiveness of public transport and the car. For illustrative purposes we represent all maps for the same study area (i.e. Matosinhos, Portugal), chosen as example for this report.

6.1. Distance/Time measure

The first example we measure accessibility to one type of destination - nearest high schools - using Time measured by the network. The following results are expressed with side-by-side and composite maps with ratio and clusters as presented in Table 7.

Table 7 - Comparative maps using distance/time measure.

	Type of measure	No. Destinations	Based on	Comparative Maps
Accessibility to nearest high schools	Time (network based)	1 type (High Schools)	Destination	Side-by-side Composite (Ratio) Composite (Clusters)

6.1.1. Side by Side

PT (Average Time: 14.3min)

Legend:

Time in minutes

0   20   >20

● High schools without access

▲ High schools with access

Car (Average Time: 3.1min)

Pop. density (res/km2)

1 - 1000

1 001 - 2 000

2 001 - 5 000

5 001 - 10 000   ETRS 89
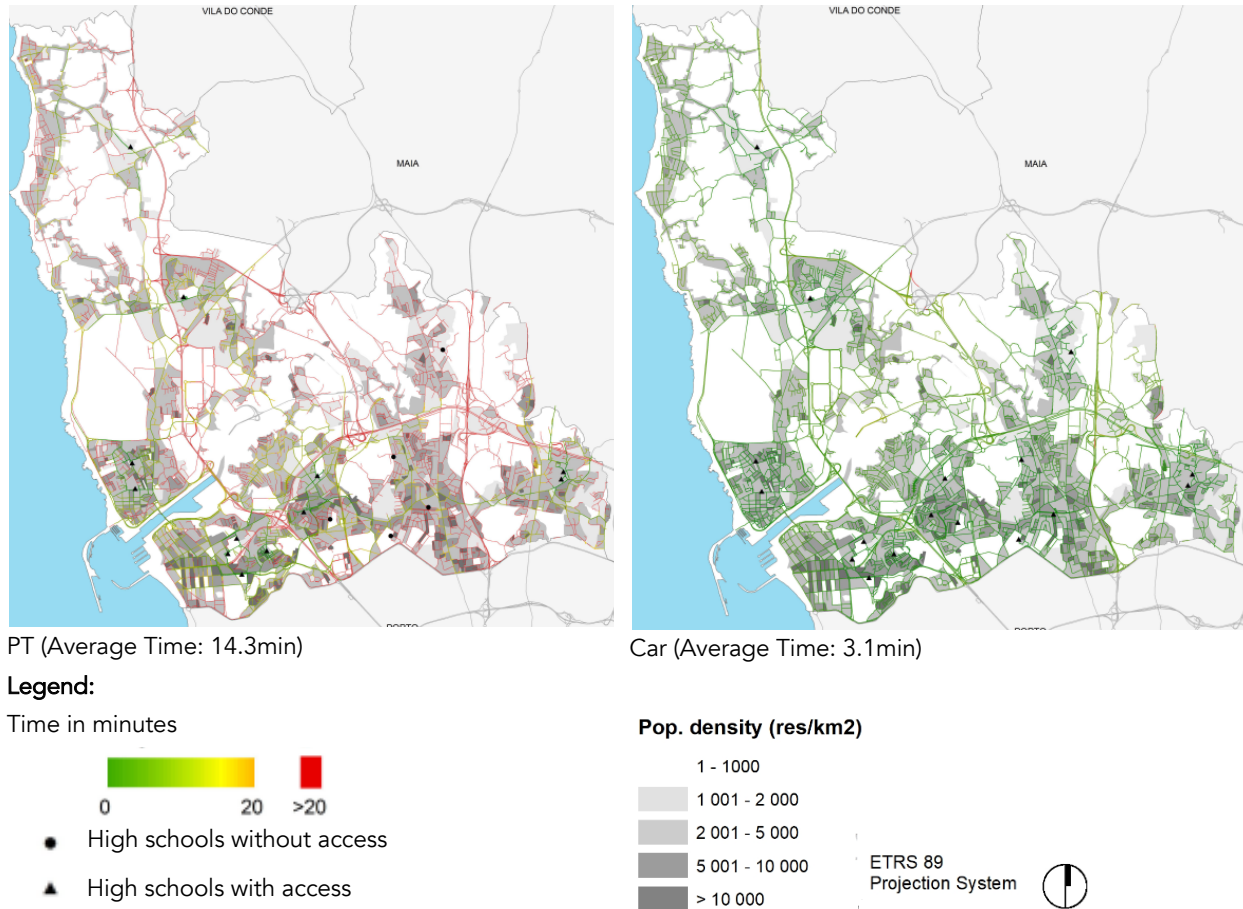   Projection System

> 10 000

Figure 7 - Time-based accessibility map. Source: Pinho et al (2016).

These maps show the time to the nearest high school by public transport (on the left) and by car (on the right), represented on the road centreline. Streets segments marked in green provide their inhabitants with travel times below 10min, while those in red require more than 20min to reach the nearest high school. By putting these simple time-based maps side-by-side it is easy to identify areas where public transport is far less efficient than the car in providing access to high schools (streets in red on the left map and in green on the right map). These maps allow for the computation of the average travel time for the whole study area. In the given example the average travel time for the nearest high school is significantly lower by car (around 3min) than by public transport (around 14min). These values translate the high inequalities of access provided by both modes across the study area. Although these aggregate values already provide a clear picture of the inequalities of access by both modes, the side-by-side maps allow for a spatial understanding of these inequalities. It is important to point out that some areas provide similar

conditions by both modes (dark green in both maps). Thus, while average values might be very different, local realities vary across different areas of the study area.

It is also important to point out that the simple overly of these maps with population density maps allow for an even deeper analysis of relative competitiveness. For instance, despite of the large number of roads with average travel times above 20min by public transport to the nearest high school, it is evident that most of these are located in scarcely populated areas. Therefore, overlaying these side-by-side analyses of time or distance-based maps with population density allows for a better understanding of the most pressingly areas in need of public transport improvements to improve its competitiveness towards the car. Relative competitiveness becomes even clearer by creating simple composite maps from these two maps, as shown in the next two sections.

6.1.2. Composite - Ratio
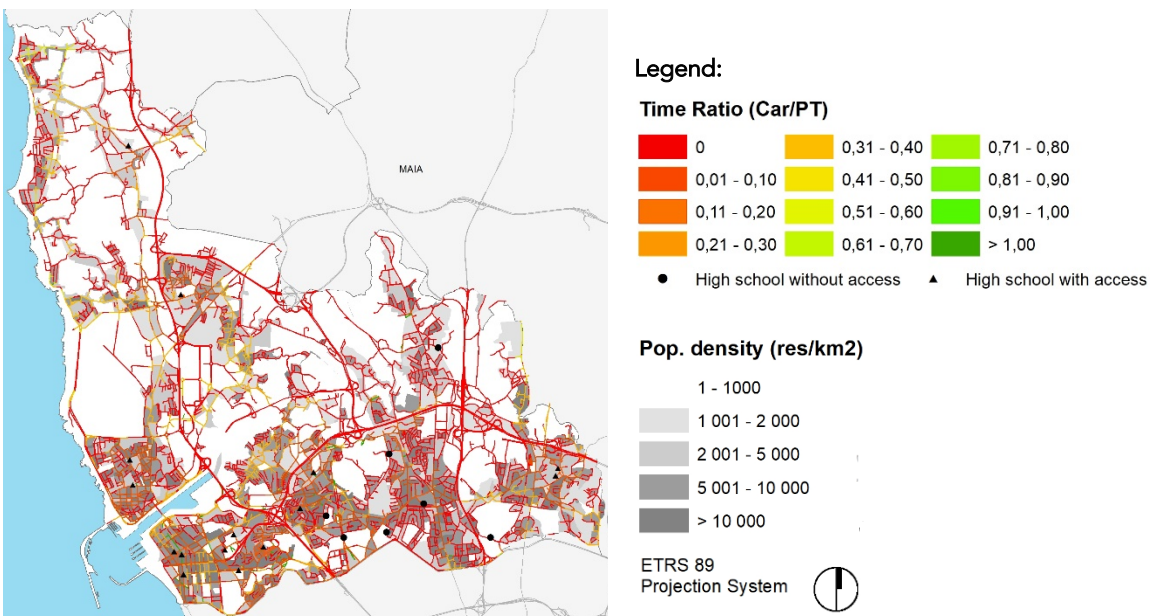
Figure 8 - Travel Time Ratio (PT/Car).

This first composite presents the simple ratio of travel time by public transport and the car, for each road section. Sections represented in dark red reveal the car to be most competitive when compared to public transport (with regard to travel time). In this case, streets without public transport service provide no access and this the ration is zero. Section in dark green would represent the opposite, however, in this example non can be found. The lighter the road section (more yellow or green) the higher the relative competitiveness of public transport when

compared to the car. Regardless, this highest competitiveness still is very limited with public transport travel times to nearest school 2 times higher than that by the car.

This composite map enables us to see both maps of Figure 7 in one single map. Again, the overlap with population density allows a quick identification of areas most pressingly needing improvements of public transport service. This map also shows that regardless of the quality and service level of the public transport service in place in this study area, the car is far more competitiveness than public transport when regarding travel time (2 time more and higher).

6.1.3. Composite - Clusters
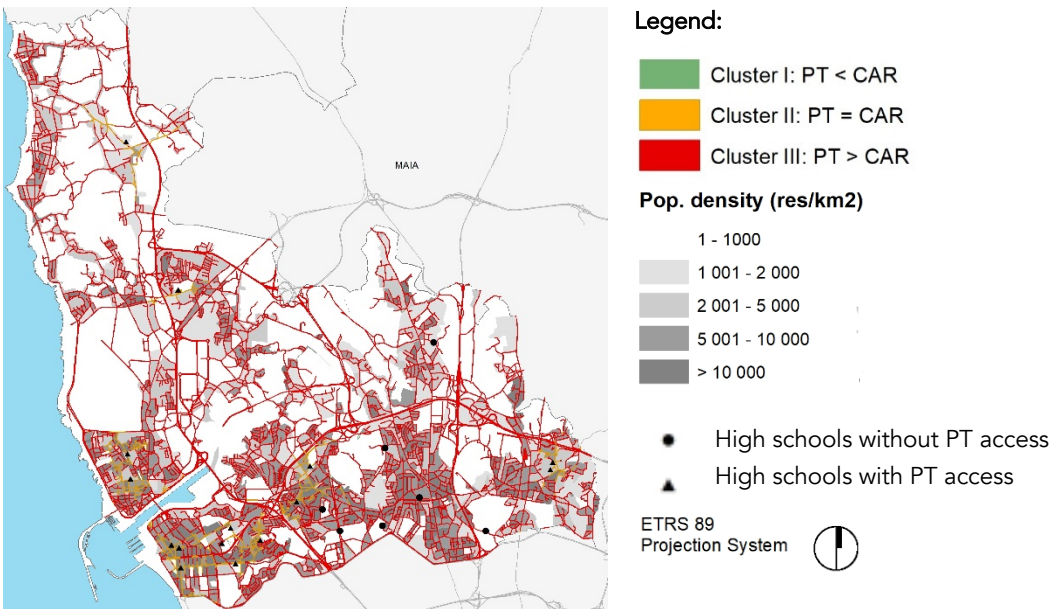
Figure 9 - Travel Time Clusters (Car/PT).

Another example of a composite map build of the maps of Figure 7 is presented in the figure above using clusters. In this example, 3 classes were defined for travel times: A) travel time below 10min, B) travel times between 10 and 20min, and C) travel times above 20min. Combinations of these classes by mode are used to define 3 clusters according to the defined below.

Table 8 - Travel Time Clusters (Car/PT) I, II and III.

Clusters		Car		
		A	B	C
PT	A			
	B			
	C			

Cluster I: PT<Car
Cluster II: PT ≈ Car
Cluster III: PT>Car

This is only one example of clusters which can be defined based on the travel times for each road segment represented in Figure 7. By creating a simpler legend for analysis, these clusters distinguish situations in which travel times are higher by PT (in red), by the car (green) or similar (yellow). Both former clusters show inequalities with regard to relative competitiveness. The first in favour of the car, and the second in favour of public transport. As expected, the latter inequality cannot be found in this study area. The last cluster, grouping street segment with similar travel times by both modes identifies areas were relative competitiveness is most similar.

By overlaying the map with population density, it becomes evident that most population lives in areas where the car provides higher competitiveness with regard to travel time. Regardless of some denser areas, seam to provide more similar conditions by both modes. Although, as seen in Figure 9, even in these cases travel times are at best twice as high by public transport than by car but at least they are both in reasonable values (below 20min).

6.2. Isochrone measure

Using the same destination, in the second example we use an isochrone of time, by both Euclidean and network distance parameters. The comparative maps are presented side-by-side, overlapping and composite (cluster) as shown in Table 9.

Table 9 - Comparative maps using isochrone measures.

	Type of measure	No. Destinations	Based on	Comparative Maps
Accessibility to nearest high schools	Isochrone (Time) based on Euclidean distance and network parameters	1 type (High Schools)	Destination	Side-by-side Overlapping Composite (clusters)

6.2.1. Side by Side

The following maps (Figure 11) show the accessible area within 20min of high schools by public transport (left) and by car (right). The first pair of maps use Euclidean distance (straight line buffers), while the second pair uses network distances. In either case, the areas with access to high schools are significantly smaller by public transport than by the car. This is due to the limited coverage of public transport in the study area. There are even schools without any access to public transport (represented by black dots instead of black triangles). Those that do have access, only provide access to areas along the public transport routes and at limited distances from stops.

PT - Euclidean Distance

Car - Euclidean Distance

PT - Network Distance

Car - Network Distance

☐ Accessible Area
● High schools without access
▲ High schools with access

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Projection System

Pop. density (res/km2)
1 - 1 000
1 001 - 2 000
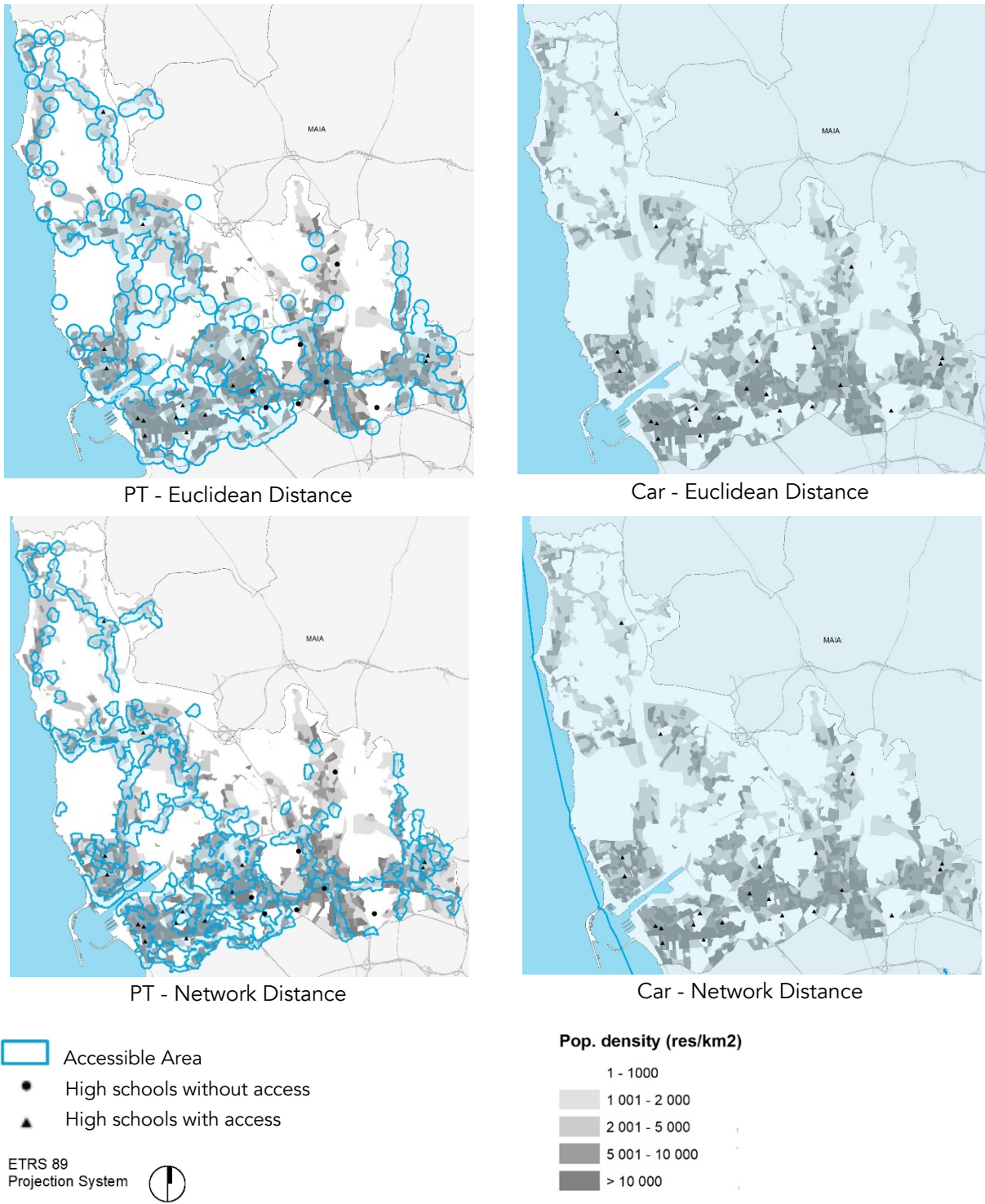2 001 - 5 000
5 001 - 10 000
> 10 000

Figure 11 - Accessible area by public transport (left) and by car (right) from high schools (20min isochrones).

It is clear that using network distances is more accurate than using regular straight-line buffers, due to the, sometimes, limited road network limiting spatial permeability. Regardless, the use of any of the option (straight-line distance or network distance) already provides rich comparisons between public transport and car-based accessibility levels. As seen in both car maps, the whole study area falls within 20min driving from a high school. Thus, by setting these simple accessibility maps side by side it is already possible to identify areas where public transport can be considered as an alternative for the car and where this is not the case. By overlaying the simple maps, once again within the information of population density, it becomes easy to identify populational areas without public transport alternatives for access to high schools.

6.2.2. Overlapping

Simple overlapping of public transport and car accessibility maps are a commonly used approach for isochrones. These maps allow a straightforward analysis of the areas with access to schools by public transport and the car or not. Considering separate maps above, and the full accessibility provided by the car in this study area, overlaying both maps (public transport and car) would provide again the public transport map, showing two situations: areas where both transport modes provide access to high schools in 20min, and areas where only the car provides access to high schools. For this reason, the overlapping of public transport and car map is the same as provided in the left maps of the Figure 11.

These maps convey the same message as discussed above but overlaying of the maps helps a clearer identification of the areas where public transport is an alternative and where not. The same message again is conveyed by the following composite map.
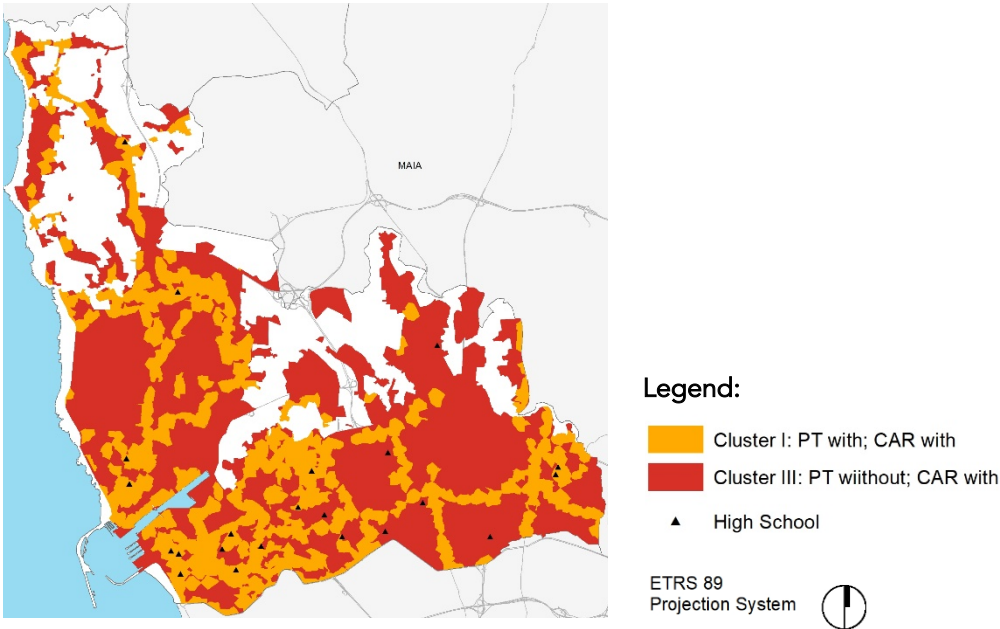
6.2.3. Composite – Clusters

Figure 12 - Accessibility Clusters: Areas with and without access to High Schools (20 min).

In the case of isochrones, we present the composite map resorting to clusters only (Figure 12). Ratios are not possible due to lack of numeric values to use ratios on. As seen below when clustering possible results of the overlay of public transport and car isochrone maps, 4 clusters are theoretically possible: I) PT providing access; CAR providing access; II) PT providing access; CAR not providing access; III) PT not providing access; CAR providing access; IV) PT not providing access; CAR not providing access.

Table 10 - Accessibility Clusters I, II, III, IV.

| Cluster I: PT with; CAR with |
| Cluster II: PT with; CAR without |
| Cluster III: PT without; CAR with |
| Cluster VI: PT without; CAR without |

Clusters		Car	
		A	B
PT	A		
	B		

Classes:

A: with access (<20min)
B: without access (>20min)

As already said in the previous sections, in this case study only two of the theoretically possible clusters are found. This map clearly reveals a large proportion of the study area as being car-dependent for high school access. Only in the orange areas (cluster I) can public transport be considered as an alternative and as such as competitive with the car. These maps can be used to identify land use policies such as disabling urban expiations to car-dependent areas, or transport policies expanding public transport services.

6.3. Contour measure

In this example, we analyse accessibility based on origin location instead of the destination (high schools) as shown in the previous examples, counting the number of activities within the accessible area, thus using a Contour measure. Assuming the geographical centre of each spatial unity (in the Portuguese case, the census tract) as the origin location, we calculate the number of accessible high schools using an isochrone reference of 20 minutes by public transport and car (same as presented in Figure 11). We present the examples with side-by-side maps and by composite maps using ratio and clusters.

Table 11 - Comparative maps using Contour measure.

Example	Type of measure	No. Destinations	Based on	Comparative Maps
Accessible high schools	Contour (Time) based on the network	1 type (High Schools)	Origin (centroid of each census tract unity)	Side-by-side Composite (Ratio) Composite (Clusters)

6.3.1. Side by side

The contour measure represented in the following Figure 13 identifies the amount of high schools accessible from each census track in 20min by public transport (left) and by car (right). As is clearly visible, most of the study area offers no accessibility to high schools by public transport (red areas in the left map). Some areas with higher concentration of schools and public transport services offer accessibility to more than 5 schools by public transport (dark green in the left map). On the other hand, the amount of accessible schools is significantly higher by car in most of the study area, providing car users higher choice on high schools, then public transport users.

PT   Car

Legend:

Number of accessible high schools

- 0
- 1
- 2 - 5
- >5

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Projection System
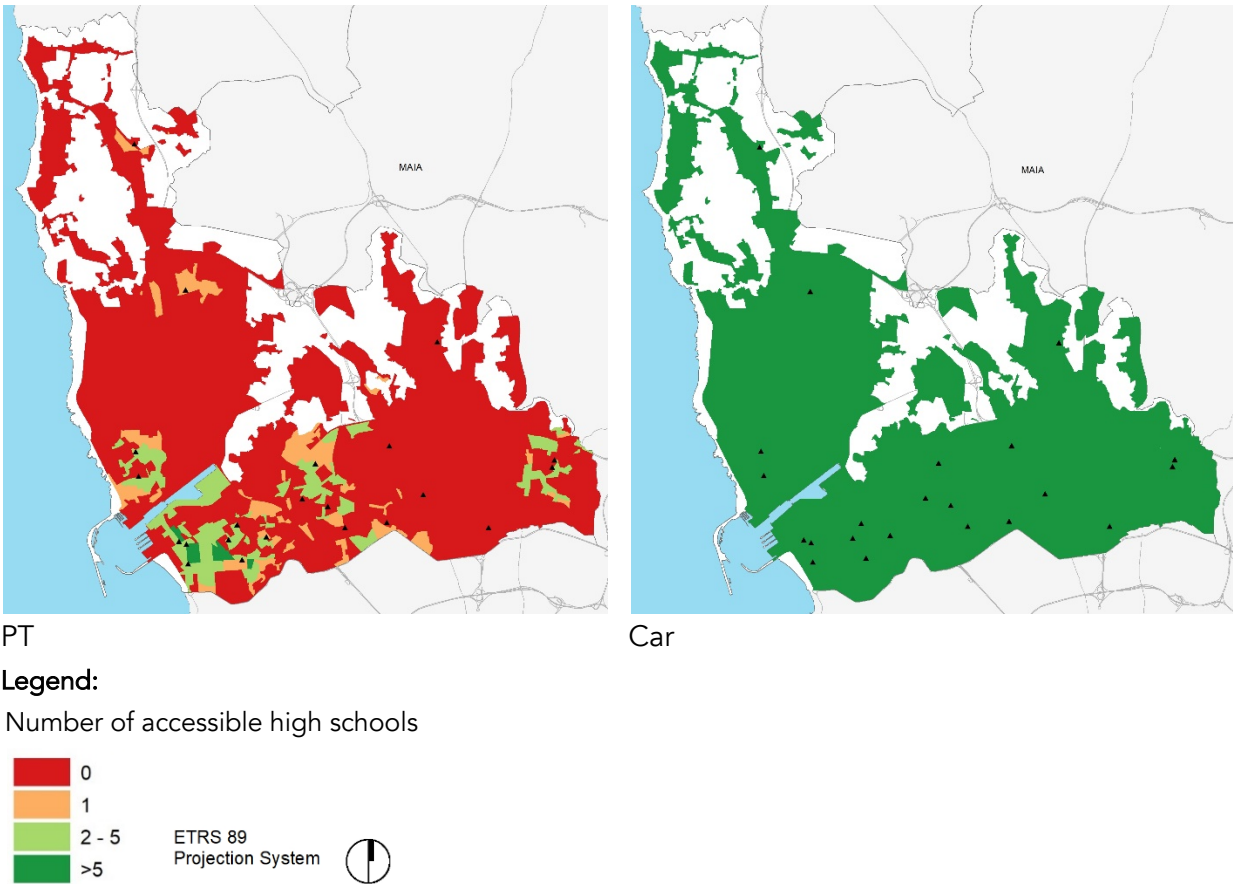
Figure 13 - No. of accessible high schools by public transport (left) and by car (right), in 20min.

Although not specified by the colour scale, the number of high schools accessible in 20min by car from the same census track reaches as high as 22, and in the worst-case scenario as low as 7. By public transport the number of accessible schools reaches between 0 and 8. This is clearly reflected in the average number of accessible schools which is below 1 by public transport and reaches as high as 19 by car (see Table 12).

Table 12 - The average population with different levels of accessibility by PT and car to accessible high schools.

Population per no. of schools accessible	PT	Car
Average no. of accessible schools	0,6	19
% of population with no schools accessible	75,5	0
% of population with 1 school accessible	8,5	0
% of population with 2-5 schools accessible	13,4	0
% of population with >5 schools accessible	2,3	100

By overlaying the maps above with population density maps it is possible to account for the amount of people living in different accessibility conditions. Table 12 shows that all the population of the study area lives in areas with access to more than 5 schools by car, offering high levels of choice to their inhabitants. On the other hand, more than 75% of the population live in areas without access to high schools by public transport. These maps and statistics allow for a better view of the limitations of public transport accessibility (in 20min) to high schools, when compared to previous approaches. In addition to the visual representation of the spatial distribution of areas without access to high schools by public transport, and its overly with population density, we now can also see that the amount of population in these conditions represent around 75% of the total population. These results make the difference between public transport and car accessibility (and thus competitiveness) more visible. Besides revealing accessibility to the closest school, it also reveals the level of choice given to inhabitants when it comes to high schools.

6.3.2. Composite - Ratio
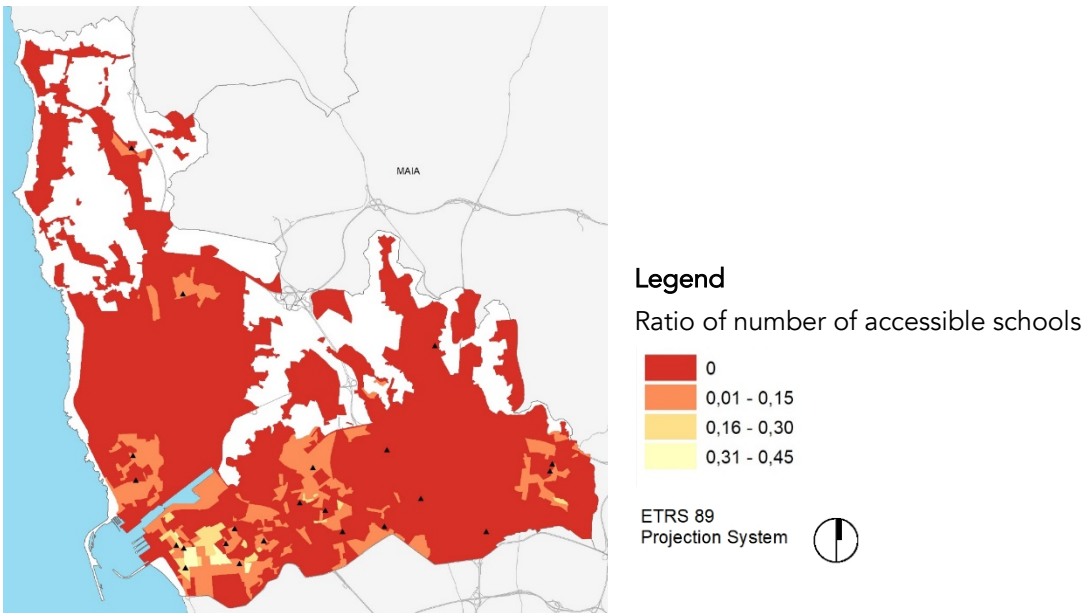
Figure 14 - Ratio of the number of accessible schools by public transport and the car.

This map represents the ratio between accessible schools by public transport and by car from each census tract, resulting from the composition of the maps of the previous figure. Areas marked in red (ratio = 0), are those without accessibility to high schools by public transport, regardless of the number of schools accessible by car. Although the vast majority of the study area shows accessibility levels by public transport lower than 15% of that by the car, a small portion of the area enables at most close to half of the high schools accessible by public transport

as those by car. This map provides a clearer illustration of de inequalities between public transport and car accessibility, highlighting the low relative competitiveness of public transport, particularly in providing choice for high schools.

Table 13 - Proportion of population for different levels of accessibility ratio.

Population per Ratio	PT/car
% of population within ratio 0	75,4
% of population within ratio 0,01 – 0,15	19,4
% of population within ratio 0,16 – 0,30	3,1
% of population within ratio 0,31 – 0,45	2,1

By overlaying the map with values of the population living in each census tract it is possible to produce some simple statistics of the proportion of the population living in different levels of competitiveness of public transport (Table 13). It clearly reveals that roughly 2% of the population live in areas where the accessibility by public transport is higher than 31% of that provided by the car. More specifically, the amount of high schools accessible by public transport are higher than 31% of those accessible by car.

6.3.3. Composite - Clusters

Figure 15 - Accessibility clusters regarding the number of accessible high schools.

Regarding the amount of high schools accessible by public transport and car, Figure 15 presents the composite map resorting to clusters. As seen in this ma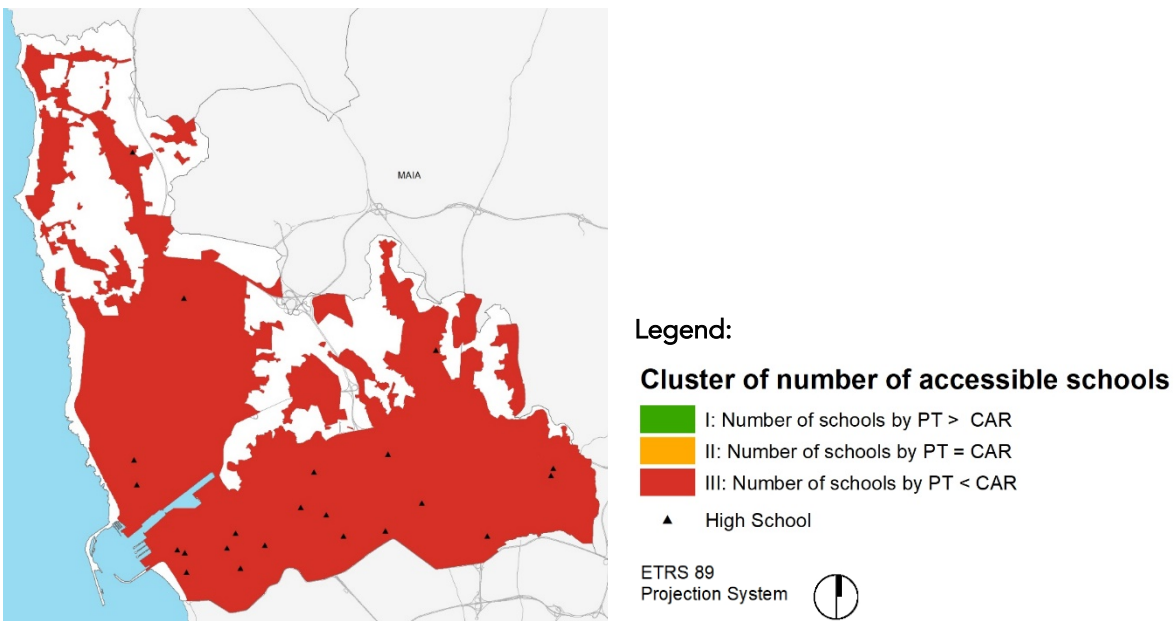p, when clustering possible results of the number of accessible high schools by public transport and the car, 3 clusters are could be suggested: I) the number of accessible schools by PT are higher than by CAR; II) the number of accessible schools by PT and by CAR are equal; III) the number of accessible schools by PT are lower than by CAR.

Table 14 - Accessibility clusters (accessible high schools) I, II and III.

| Cluster I: number of schools by PT>Car |
| Cluster II: number of schools by PT = Car |
| Cluster III: number of schools by PT<Car |

Clusters		Car	
		A	B
PT	A		
	B		

Classes:
A: with access (<20min)
B: without access (>20min)

Table 15 - Proportion of population by cluster.

Proportion of population	%
% of population within cluster I	0
% of population within cluster II	0
% of population within cluster III	100

6.4.   Contour measure (Multi-destination)

Still using a Contour measure, based on (all) origin location(s) of the study area, we now analyse accessibility to several types of destination (18 types of activities) instead of only one destination type as shown in the previous examples. This approach account not the overall number of activities but the number of activity types accessible, revealing how diverse is a certain area. In the next sections we present the examples with side-by-side maps and by composite maps using ratio and clusters.

Table 16 - Comparative maps using Contour measure (multi-destination).

	Type of measure	No. Destinations	Based on	Comparative Maps
Diversity of Activity to several destinations	Contour (Time) based on the network	18 types of activities	Origin (centroid of each census tract unity)	Side-by-side Composite (Ratio) Composite (Clusters)

6.4.1. Side by Side

PT

CAR

Legend:

Diversity of accessible activities (0 – none; 1 – all)

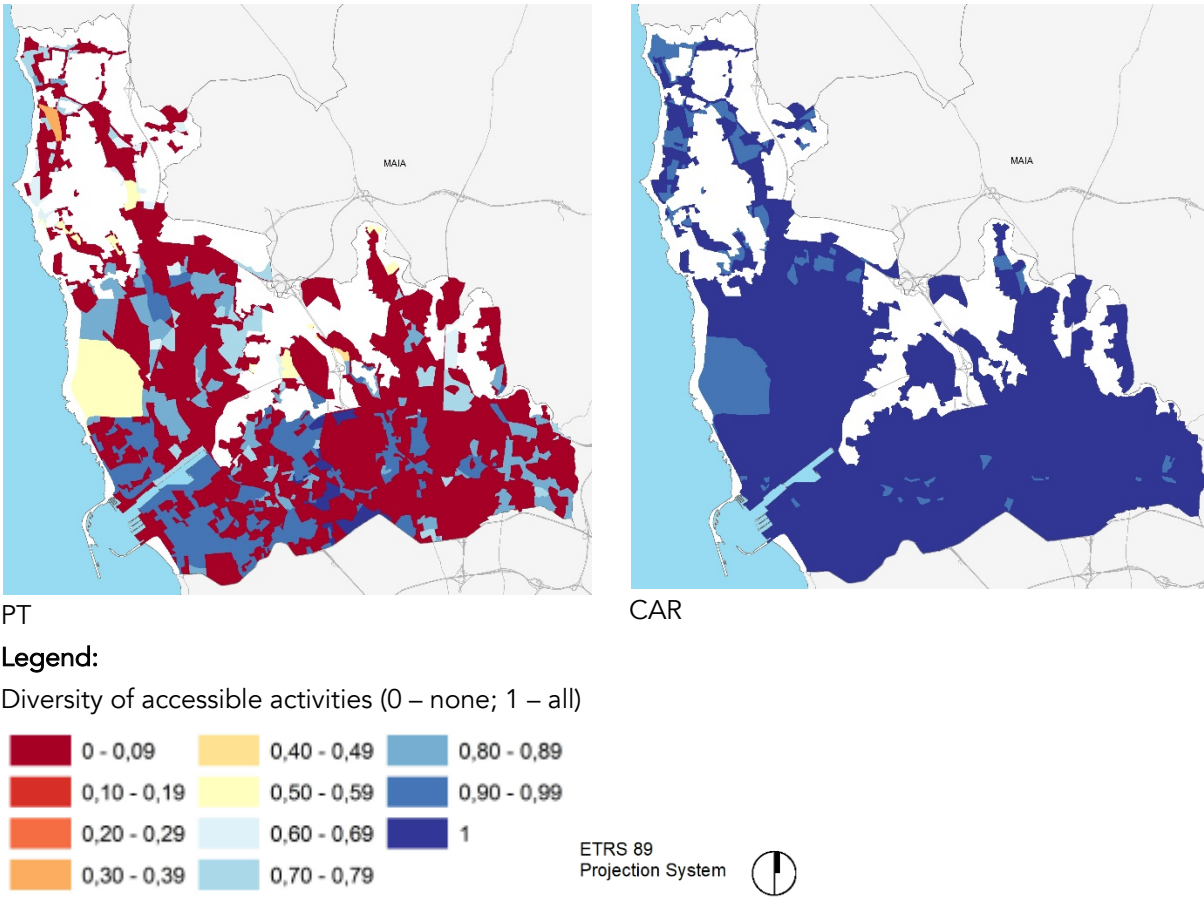|	
0 - 0,09	0,40 - 0,49	0,80 - 0,89
0,10 - 0,19	0,50 - 0,59	0,90 - 0,99
0,20 - 0,29	0,60 - 0,69	1
0,30 - 0,39	0,70 - 0,79	

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Figure 16 - Diversity of Accessible Activities (The Structural Accessibility Layer – Silva & Pinho, 2010).

As said, this last example uses the same measure as in the previous example of contour measure but goes a step further by considering multiple destinations in a single measure. This figure uses the measure of Diversity of Activities from the Structural Accessibility Layer of Silva and Pinho (2010). This measure does not count the amount of activities accessible but the diversity of those activities. In total, this assessment considered 18 different activities (including, schools, shopping, leisure, etc.). Measures such as the ones used in the prior example are part of this analysis combined into a composite measure.

The diversity of activity index counts the amount of activity types found within the 20min isochrones by both modes. These values are normalized into a scale from 0 (no activities accessible) to 1 (all activity types accessible). These are no longer simple accessibility measure despite using basic accessibility measures (contour measures).

When represented side by side, this measure shows areas with higher and lower diversity of activities accessible by both modes. Again, it becomes clear that levels of accessibility by the car are always higher than by public transport, in this case, with regard to diversity of activities accessible. Once more, diverse spatial realities are clearly visible.

By overlaying the maps with data on population by census track aggregate data can be computed as presented in the Table 17 below. The average diversity of activity levels reachable by the car is 1 (all activities reachable in 20min). On the other hand, the average diversity of activity levels reachable by public transport is 0.38. It is clear that accessibility levels are significantly lower by public transport. Also, while all population in the study are lives in areas with high accessibility levels by car, only 33% live in similar conditions provided by public transport.

Table 17 - Comparison of public transport and car and Diversity of Activity Levels.

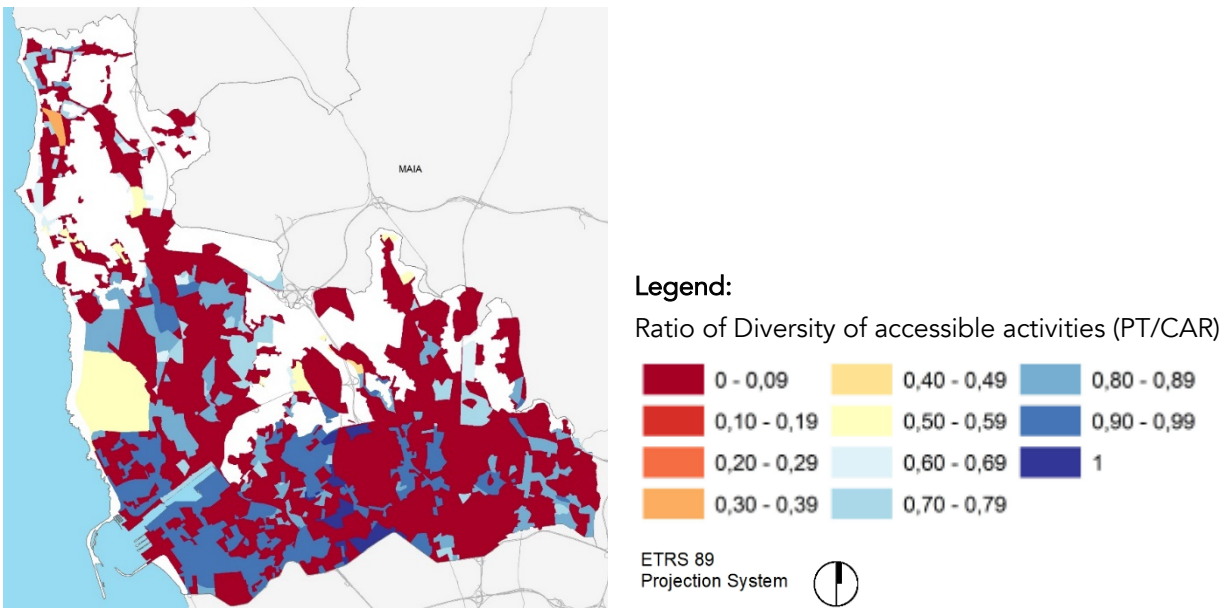| Diversity of Activity	PT	CAR
Average accessible diversity	0,38	1,00
% of population with High Accessibility: DivAct > 0.85	32,5	100

6.4.2. Composite - Ratio

Figure 17 - Ratio of Diversity of Activities Accessible (PT/CAR).

As with previous indicators, this measure enables the computation of ratio (PT/Car accessibility) maps. However, since this example shows mainly car accessibility levels of 1 (or close to 1), ratios between public transport and car accessibility are generally the same as public transport accessibility. And so, Figure 18 is similar to the left map of Figure 16. As in the previous indicator, we apply the overlap with the population living in each census tract. The proportion of the population that lives at different levels of competitiveness of public transport compared to the car is shown in Table 18.

Table 18 - Proportion of Population for different Ratio levels.

Population for Ratio level	%
% of population within Ratio 0 – 0,09	56,7
% of population within Ratio 0,10 -0,19	0
% of population within Ratio 0,20 – 0,29	0
% of population within Ratio 0,30 – 0,39	0,2
% of population within Ratio 0,40 – 0,49	0
% of population within Ratio 0,50 – 0,59	0,8
% of population within Ratio 0,60 – 0,69	1,6
% of population within Ratio 0,70 – 0,79	3,6
% of population within Ratio 0,80 – 0,89	9,9
% of population within Ratio 0,90 – 0.99	25,2
% of population with Ratio 1	1,9

6.4.3. Composite – Clusters

The Structural Accessibility Layer defines 7 theoretical clusters for 3 the comparison of 3 transport modes (non-motorized, public transport and car). For 2 transport modes these clusters are simplified into 4 as presented below: I) high accessibility levels by PT and the Car; II) high accessibility levels only by PT; III) high accessibility levels only by Car; IV) low accessibility levels by PT and the Car.

Table 19 – Clusters of Accessible Activities.

Cluster I: PT high; CAR high
Cluster II: PT high; CAR not high
Cluster III: PT not high; CAR high
Cluster VI: PT not high; CAR not high

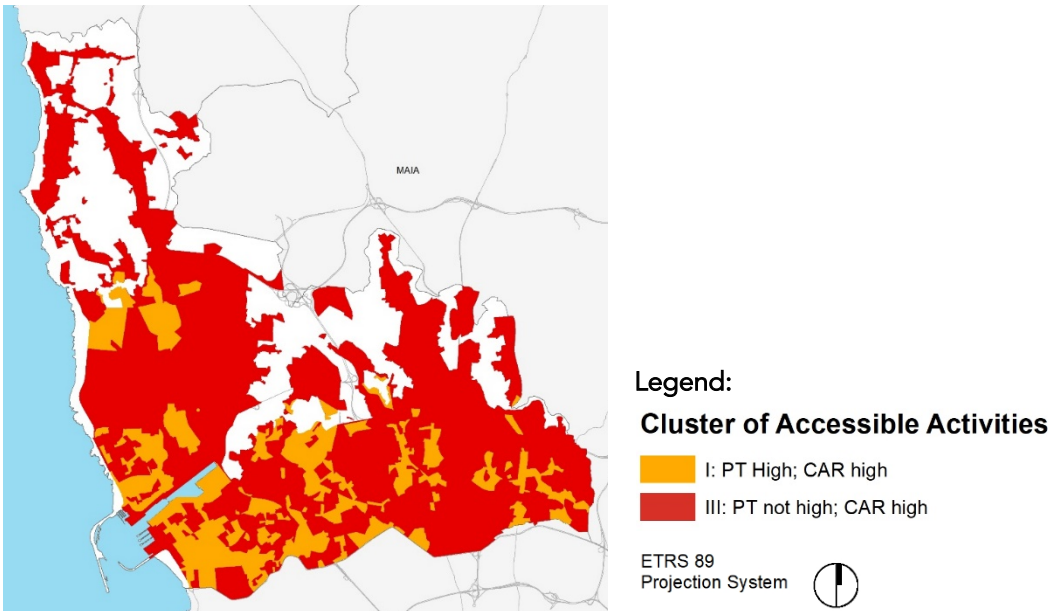| Clusters		Car	
		A	B
PT	A		
	B		

Figure 18 - Cluster of Accessible Activities.

This map clearly shows the areas which offers high diversity of accessible activities by both modes (in orange). These areas are those where the public transport offers similar competitiveness to the car by allowing similar range of choice of accessible activities. However, the majority of the study area registers only high accessibility levels by the car (in red), clearly identifying car-dependent areas. As shown in Table 20, 67% of the population live in these car-dependent areas. These maps, highlight the importance of avoiding large urban developments in car-dependent areas, if public transport expansions are not implemented as well, at the risk to increase the amount of population living in car-dependent conditions.

Table 20 - Proportion of population by Cluster.

Population per Cluster	%
% of population in Cluster I	32,5
% of population in Cluster II	0
% of population in Cluster III	67,5
% of population in Cluster IV	0

7. Using Relative Competitiveness in planning practice

The set of accessibility indicators proposed in the previous section, for revealing relative competitiveness of public transport and the car, can be used to support different strategic decisions in planning practice. These can be used as an diagnostics tool, as thoroughly explored in the previous section, identifying spatial inequalities regarding travel time, distance or cost by public transport and the car, to different destinations. These analyses can easily reveal shortcomings of the land use and transport systems, such as, the ill distribution of residential areas and destinations (such as employment, schools, hospitals, etc.), or the limited spatial coverage of public transport. While clearly highlighting areas with larger weaknesses in public transport competitiveness, these indicators can also be used to simulate effect on public transport competitiveness following land use and transport policies under consideration.

Starting with transport investments, it is clear that, the assessment of effect on public transport competitiveness prior to any public transport investments, would be of the utmost importance to ensure relative competitiveness is taken into consideration. It is frequently the case that public transport investments pursue minimum service levels, underrating the low competitiveness of public transport services provided. Although these investments provide higher levels of public transport coverage, they do so mostly at the expense of transport service quality and thus providing very low competitiveness when compared to the car. These services are thus intended for car-less riders (also called *captive riders* by van Lierop and El-Geneidy, 2016) and not at encouraging a shift from car users to public transport (also called *choice riders* by van Lierop and El-Geneidy, 2016). Resorting to tools, as the ones suggested in the previous section, would enable a clear assessment of the effects of any new public transport investments on relative competitiveness. In addition to enabling assessments of the improvements in public transport service level, composite maps allow for an assessment the improvement of public transport competitiveness in relation to the car. These analyses reveal the potential efficiency in bringing about modal shift.

These assessments are not only relevant for public transport investment but for, virtually, any policy regarding the mobility system. Particularly, changes in road infrastructure or service level would greatly benefit from such assessments. These would reveal the impact of building new road link, or reducing congestion in another, on the relative competitiveness of public transport. It is important to point out that, regardless of the investments made in public transport, relative competitiveness of this transport mode can be severely reduced simply by improving the competitiveness of the car. Thus, these indicators are important in assessing both public transport and road investments.

Finally, but not less important, is the potential of revealing the relative competitiveness of public transport following land use policies or plans. As clearly visible, in the examples provided in the previous section, relative competitiveness of public transport compared to the car depends on how well these modes provide access to certain opportunities/activities. It is clear that, this access depends on the spatial distribution of population densities and of destinations. Thus, urban policies concerning urban expansion or location of new public facilities (such as schools, hospitals, etc.) should also be accompanied by the assessment of the relative competitiveness of public transport services. Revealing relative competitiveness brings relevant foresight on the impacts of land use investments on travel behaviour. At the same time as it also reveals the need for integrated land use and transport planning to bring about more sustainable travel behaviour. This is particularly important in traditionally segregated planning contexts, where land use plans and public facilities are decided mostly without regarding public transport system. Revealing relative competitiveness during land use planning would enable a discussion around the full cost of urban sprawl and of placing public facilities (such as schools and hospitals) at the edge of urban areas (resorting to less expensive land), to cite only two examples.

In summary, revealing relative competitiveness of public transport and the car is not only possible through relatively simple accessibility measure (see section 6) but also of the utmost importance in supporting integrated land use and transport planning encouraging more sustainable mobility.

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