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ORIGINAL PAPER

Working with the daily variation in infrastructure performance on territorial accessibility. The cases of Madrid and Barcelona

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Abstract

Purpose Accessibility measurements are good tools for analysing the performance of possible policies on land use / transport / society systems. Until now, accessibility has been approached from a static perspective, even when variations in it depend on short term temporal changes in network function. Solutions based on static measurements, with journey costs taken as units based on free-flow travel time; do not reflect real network performance at different times of the day.

Methods In order to broaden our understanding of accessibility and study real-world dynamism in depth, information from new sources has been incorporated into traditional accessibility measurements, with actual observed data on the daily variations in speed profiles. These variations have been used to assess the impact of congestion on accessibility, with dynamic scenarios calculated every 15 min.

Results The variations in daily accessibility in the metropolitan areas of Madrid and Barcelona (Spain) have been mapped with reasonable computational costs. Although both cities have a similar global behaviour pattern, each has a different daily spatial accessibility distribution. Madrid appears to be more resilient than Barcelona.

Conclusions With new technologies it is possible to overcome previous technical barriers, such as the lack of reliable information or calculating capacity. An ordinary computer has been used to obtain complete and detailed temporal profiles of the two traditional accessibility measurements. Thanks to these new measurements, we have a better understanding of accessibility. However, in order to express a dynamic phenomenon in static format, appropriate mapping schemes would have to be devised.

Keywords Daily accessibility · Dynamic impedance · GNSS · GIS

1 Introduction

In recent decades, the concept of accessibility has gradually gained importance. It has proved to be a useful tool for understanding the functioning of land use / transport / society systems and also for measuring the scope of human activity relations at territorial level. Accessibility is one element to consider in decision-making involving any action or policy that may influence the performance of this system. This is how it has been understood by numerous governments, who have incorporated accessibility in their territorial planning policies. Among the examples most frequently quoted are those of the Netherlands, with their ABC philosophy [1], the United Kingdom, which introduced accessibility as a strategic objective in its national policy in 1994 [2], and the European Union, which includes accessibility as an objective in its spatial development perspective [3].

Although accessibility is a widely used concept in various fields of science, it is usually misunderstood [4] and may even

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be confused with mobility [5]. In reality, mobility is one of the results of accessibility. The source of this confusion lies in the fact that there is no single unanimous definition of the concept of accessibility. On the contrary, numerous definitions can be found in literature. One of the most frequent is *the ease with which activities can be reached, given a location, using a specific transport system* [6]*, or the ease of interaction with a significant number of opportunities* [7–9]. Most definitions emphasise the role of accessibility as a territorial potentiality, implying that its values are a consequence of the complex system based on human activities. In any case, accessibility can be said to be much more than just the main product of the transport system as Schümann and Talaat have proposed [10].

Any change in one of the components of the land use / transport / society system would therefore have an impact on accessibility and at the same time generate reactions in the rest of the components and their relationships. By analysing how accessibility changes at different times or scenarios, it is possible to measure these impacts and know the effects of changes on transport networks, such as the construction of new transport infrastructures, new transport policies and regulations, the evolution of actual traffic flows and the standard of service throughout the network. At the same time, accessibility is also influenced by changes in the location of economic activities (such as changes brought about by new activities or the relocation of existing ones, or changes in the attractiveness of the destination), as well as the impacts of societal changes in habits, capacities or willingness to travel. The usual procedure for measuring the impact of these changes on accessibility is to compare values and their spatial distribution before and after the change being studied. For example, to assess the impact of the construction of a motorway, a comparison of the scenario with and without the motorway is made, while the rest of the components, which are not being studied, are kept constant. This makes it possible to isolate the effect of change on the transport network [11].

This same scenario-based methodology has previously been used to study the effects of congestion on accessibility. In this case, two standard traffic scenarios were compared, one at off-peak times and the other with rush-hour traffic [12]. However, comparison of these two scenarios may not be appropriate because neither of them captures the temporal change in infrastructure performance. To do these studies properly it is necessary to use a dynamic approach that incorporates the temporal sequence of network speeds with increases and reductions in traffic volume. Unfortunately, one of the main problems of using dynamic accessibility measurements is the difficulty in obtaining the required information on speeds. The lack of data and the fact that either estimated or unreliable speeds are used may distort the results and could lead to wrong conclusions.

Fortunately, it is possible with today's new technologies to obtain information that was previously unattainable, as well as work with ever larger databases. For instance, thanks to devices with GPS location technology, reliable information can be obtained on speed variations observed in infrastructure performance [13]. The use of these new sources of information and the greater processing capacity of computers has enabled detailed studies of dynamic accessibility in large metropolitan areas to be carried out. As a result, the causes of most of the secondary effects of accessibility on different planning actions or policies are beginning to be understood, such as possible temporal effects based on Braess's paradox ([14] translated from [15]), which cannot be properly estimated with traditional static accessibility measurements.

This article studies how to introduce information on the variation in transport infrastructure performances through changes in speed in the road network during the course of the day. Big data information incorporated in a GIS environment has been used (in this case TomTom® Historical Speed Profiles) with the aim of calculating the variation in accessibility every 15 min on a typical mid-week day. The proposed methodology has been tested on Spain's two most populous metropolitan areas, Madrid and Barcelona. Results based on their respective accessibility profiles show differences between the two cities in both global variation and territorial and temporal distribution.

The article is laid out as follows: After the introduction, Section 2 is a brief review of accessibility measurements and how to adapt them to make the leap to studying temporal variations in infrastructure performances. Section 3 presents the areas of study, the data used and computational specifications. The results are shown in Section 4. The final section is a discussion of the conclusions and possible steps to be taken in future research, with the aim of making use of all the new information.

2 From static to dynamic accessibility. Some approaches

Authors of previous studies have proposed different methods to measure accessibility. As with the definitions of accessibility, each proposal depends on which element of the land use / transport / society system is being emphasised, as well as on the information available [16] and/or on computational capacity. There are therefore numerous proposals for classifying the different methodologies used. Geurs and Ritsema van Eck [17], for example, classify accessibility measurements into three major categories: those based on infrastructures (levels of service), those based on activities (the number of jobs less than 30 min away, or the number of activities a person can carry out in a maximum period of time), and those based on utility (accessibility considering individual preferences according to discrete choice theory). Other classifications of interest can be found in Morris, Dumble and Wigan [6];

Reggiani [18]; Bruisman and Rietveld [7]; Handy and Niemeier [19]; Geurs and van Wee [4]; Curl, Nelson and Anable [20]; and Paez, Scott and Morency [21].

2.1 Two approaches to measuring accessibility

The challenge presented by different methodologies for measuring accessibility, as with any other measurement, is to fulfil two basic requirements: the degree of confidence and consistency of the measurement with observed behaviour (*soundness*), and the transparency and simplicity of calculation procedures and their capacity for communicating results (*plainness*) [22]. While maintaining these two requisites, two classic static accessibility measurements are modified in this article in order to capture the dynamism of changes in daily network functioning. The measurements used are *average weighted impedance* and *potential accessibility*. Their definitions each incorporate both transport system performances and the spatial distribution of opportunities.

The *average weighted impedance* [23] calculates accessibility for each zone of origin as the average impedance (e.g. time or cost) of reaching all destinations within the study area. The importance of the opportunities at destination (e.g. population, employment or GDP) weights for each Origin-Destination impedance. The obtained results are very simple to understand, even for non-experts: any location with low average impedance is near destinations and their opportunities. For each origin, this average weighted impedance is calculated as follows:

$$\dot{c}_i = \frac{\sum_{j\in N} D_j \cdot c_{ij}}{\sum_{j\in N} D_j}; \forall i\in N \tag{A}$$

Where:

$\dot{c}_i$ is the average weighted impedance of zone i
c_{ij} is the impedance of travelling from zone i to zone j
D_j is the weight or potential of zone j
N represents all zones included in the study area

However, it should be pointed out that this accessibility measurement has certain determinants and that it is necessary to be aware of these, otherwise its soundness and plainness may be obscured. Firstly, this indicator requires a complete impedance matrix: that is, all origins must reach all destinations. Working with unviable relationships introduces anomalous values that may lead to erroneous interpretations. Secondly, results of this measurement are closely linked to the definition of the study area, especially in peripheral zones. For example, there may be a great distance between origins and concentrations of opportunities, with hardly any relationship between them. Nevertheless, the presence of these distant opportunities would affect the accessibility value. This shortcoming could partially be fixed by imposing a predefined impedance threshold. Finally, because results are expressed in units of travel costs, the *average weighted impedance* may easily be misinterpreted as exclusively measuring transport system performance, while other components, , e.g. the spatial distribution of opportunities and its amount, are ignored.

The second used measurement, the *potential accessibility*, is based on the definition given by Hansen [9]. This measurement can be interpreted as the sum of the *equivalent perceived opportunities reachable* from an origin, since the weight of any destination decreases as impedance increases. As a result of this definition, a large concentration of opportunities in a distant location may be perceived as being as attractive as another location nearer the point of origin but with fewer opportunities. Traditionally, the result has been measured in units called *Market Potential Units (MPUs)*. It should be noted that one of the strengths of this measurement is that any unreachable zone per origin does not introduce any anomalous values; their opportunities are not taken into account. The general equation for calculating potential accessibility is as follows:

$$PA_i = \sum_{j\in N} D_j \cdot f\left(c_{ij}\right); \forall i\in N \tag{B}$$

in which

PA_i is the potential accessibility value of zone i
D_j is the potential of zone j
$f(c_{ij})$ is the impedance-decay function
c_{ij} is the impedance of travelling from zone i to zone j
N represents all the zones included in the study area

The *potential accessibility* is also influenced by the area chosen for the study. There are some opportunities outside that region that may strongly influence the accessibility values, especially in the border region. In order to fix this problem, we should expand our area of calculation beyond borders, including also all opportunities inside the surrounding buffer area of our study area and calculate the impedances between each origin in our study region and these opportunities as destination. On the other hand, when it comes to comparing different spaces (such countries, regions or cities), this method may lead to erroneous conclusions since results depend to a great extent on the total number of opportunities within the study area.

2.2 Moving through the transport network. Static impedances and dynamic impedances

Irrespective of the type of measurement, estimation of the transport component is essential for studying accessibility. The transport network shapes real distances or impedances within the study areas. Thanks to transport networks, distant locations can be reached more rapidly or more cheaply than others that may be nearer but which are badly connected. Traditionally, impedance has been measured as a single constant value for any origin-destination relationship and calculation scenario (which usually corresponds to the lowest cost route). The value of the static type of impedance is defined by the following equation:

$$c_{ij} = \sum\nolimits_{e \in E} \alpha_{eij} \cdot c_e; \forall ij \in G \tag{C}$$

where

c_{ij}	is the impedance of travelling between zone i and zone j, the value of which is invariable in time
α_{eij}	is the binary variable that indicates whether arc e is used in the journey between zone i and zone j
c_e	is the impedance of arc e, which is predetermined and constant
G	is the set of origin-destination relationships
E	is the set of arcs in the study area network

By definition, static impedances omit the possible variation in infrastructure performance experienced by any vehicle travelling in a particular calculation scenario. This type of measurement is, therefore, only appropriate for studies in which these internal-scenario variations are irrelevant, such as the comparison of scenarios for two different years in the same country. On the other hand, the study of dynamic phenomena, such as changes in accessibility in an urban space during the course of the day, cannot be carried out satisfactorily with static methods [24]. In these studies, impedances not only depend on which scenario is calculated or on journey departure time, but also on when each arc is used. Figure 1 shows an example of the difference between the shortest route estimated by static methods and dynamic methods for a vehicle that begins its journey at 09.00 h. The weights of each arc are expressed in minutes and it is assumed that information on the state of the network is given every 5 min. The static method estimates the cost between origin and destination to be 11 min, although the vehicle will really take 10 min because when it arrives at the third arc, its cost will have decreased. In contrast, the route estimated by dynamic methods has an impedance of 9 min.

Impedances estimated by static methods may be considered as simplifications of those obtained by dynamic methods (instantaneous travel time vs. experienced travel time [25]). Calculation of dynamic impedances is shown in equation D:

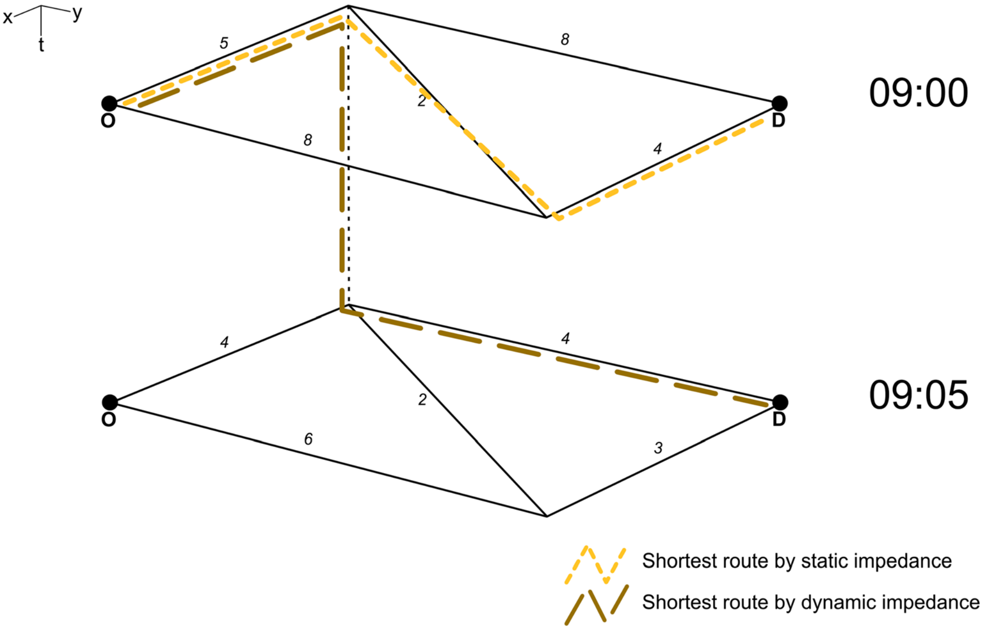
$$c_{ij}^{t} = \sum\nolimits_{m \in M} \sum\nolimits_{e \in E} \alpha_{eij}^{tm} \cdot c_e^{m}; \forall ij \in G, t \in T \tag{D}$$

Where:

c_{ij}^{t}	is the impedance experienced when travelling from zone i to zone j, beginning at instant t
α_{eij}^{tm}	is the binary variable that indicates whether arc e, use of which begins at instant m, is used for the journey between zone i and zone j which has begun at instant t
c_e^{m}	is the expected impedance of arc e, use of which begins at instant m
T	is the set of instants of started journeys
G	is the set of origin-destination relationships
E	is set of arcs in the study area network
M	is the all possible instants within the scenario

There are some complications to be taken into account when working with dynamic impedances. In the first place, as it has already been mentioned, there is the difficulty of obtaining the information required for each arc and at each instant. However, nowadays this information can be obtained from simulations [26] or from information provided by users

Fig. 1 Example of the differences between the shortest route estimated by static methods and by dynamic methods



willing to share tracks from their navigational devices. In this case, the information may be sold by major navigational companies. These huge databases are usually expensive or not accessible for all the network of our study area. On the other hand, unlike static routes, dynamic routes may require that at some point in the journey it is more appropriate to wait or use a sequence of arcs with fewer performances in order to avoid high costs in "downstream" arcs, which should be used if another more attractive sequence of arcs in a previous instant is selected. This runs contrary to the observations made by Dijkstra for defining his search algorithm of the lowest cost paths in static situations [27]. Fortunately, there are very specific dynamic routes that can be studied by trivial changes in Dijkstra algorithm [28, 29]. These algorithms finds routes by solving as many static scenarios as temporal performance description have the study network (Fig. 1). The dynamic routes which starting time is known, without overtaking and its unique target is arriving as soon as possible -as used on this paper-, can be calculated by these modificated Dijsktra's algorithms.

3 Estimation of dynamic territorial accessibility. testing in Madrid and Barcelona

As already indicated, computational capacity could have been proved to be a great barrier by many studies. The problem here comes from the underlying complexity of finding the shortest route for every Origin-Destination pair in a dynamic way in a network containing a great quantity of detail. These problems are interrelated, since a greater quantity of information and detail involves greater computational cost. The correct choice of the data to be treated, and of the software and processes to use, is therefore no trivial matter. We chose Madrid and Barcelona to prove the feasibility of a study on the daily variation of accessibility in two large metropolitan areas. In this section, aspects are outlined related to the network used and its previous processing (for example, simplification), the definition of the scope of the study (so that the settings are comparable) and the specifications of the accessibility analysis. In order to avoid possible biases in the results and the comparison between cities, we used the available data for each study area from the very same source and very same methodology per each feature.

3.1 The road network

This study has used the March 2013 version of TomTom® for the Spanish road network, together with information on *Historical Speed Profiles* for the years 2011 and 2012 obtained from the average journey times reported from users' navigation devices. As the original network is very detailed (it includes accesses to car parks, pedestrianised streets, residential streets and country roads), arcs where not much traffic is expected have been omitted. The arcs used in the study are defined by TomTom® as ranging from 0 to 6 in the Functional Road Classification (FRC).[1] The network used has full connectivity, with a total of 3,969,483 one-way arcs representing 300,122.2528 km, of which 46.48 % also have historic speed profiles. The entire Spanish network has been used so that the estimated route is always the shortest, even if this requires the use of arcs outside the study area.

The Historic Speed Profiles are defined as a percentage every 5 min with respect to the observed free-flow speed of the arc. As a result, an arc of a motorway and an arc of a city street may both have the same speed profile but have different speeds at the same instant because of their different free-flow speeds. This data structure saves on computational memory and cost and is prepared so that it can be used with the GIS software (ESRI® ArcGIS).

3.2 Areas of study: Madrid and Barcelona

The definition of the limits of metropolitan areas is usually not unique and it might even be confusing. In this article, the metropolitan area is taken to be all the towns (LAU2 [30] in Eurostat terminology) that have more than 50 % of their municipal territory within a density isoline of 500 inhabitants/km^2 from the main city. This isoline was generated with the density kernel tool,[2] using the 1 km^2 EEA reference grid [31] with Eurostat population data from 2006 [32]. It was limited to those municipalities that formed part of the Functional Urban Area (FUA, [33]) of the main city or a town completely surrounded by it. With this delimitation, we obtained study areas with demarcation criteria for opportunities and similar relationships, adapted to the study of congestion.

As a result, the Madrid study area has 5,502,282 inhabitants (representing the sum total of potential values of the areas) / 2312 km^2 / 39 municipalities and the metropolitan area of Barcelona has 4,277,836 inhabitants / 1420 km^2 / 88 municipalities.

The use of municipalities as origins and destinations may be inappropriate for performing a good spatial analysis, as there are few resulting relationships. Moreover, the use of the EEA reference grid to estimate accessibility involves excessive computational load, which makes the present study unfeasible, despite the use of a standard grid overcomes the modifiable areal unit problem (MAUP). It was therefore decided to use an intermediate grouping, with 2×2 km cells

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[1] TomTom®'s FRC Definitions. FRC 0: Motorway, Freeway, or Other Major Road; FRC 1: a Major Road Less Important than a Motorway; FRC 2: Other Major Road; FRC 3: Secondary Road; FRC 4: Local Connecting Road; FRC 5: Local Road of High Importance; FRC 6: Local Road; FRC 7: Local Road of Minor Importance; FRC 8: Other Roads.

[2] Density kernel is a tool of ArcToolBox of ArcGIS; the search radius used to estimate the values was 5.000 and 10.000 m

obtained from the 1 × 1 km EEA grid. This resulted in Madrid having 490 zones of origin and destination and Barcelona 344. This number was derived from the grouping shown and the exclusion of cells that have no network arc in their area (which would leave them disconnected). In any case, the origins and destinations considered represent 99.9 % of the population in each metropolitan area.

Finally, in order to reduce some of the problems derived from the effects of demarcation on the study areas (border effects), the total size of the area of calculation was extended to all cells outside the previous demarcation that could be reached from an origin in the study area in less than 15 min (with free-flow speeds). The use of these cells avoids the effects of the demarcation border on origins within the study area and makes it possible to produce raster maps without large distortions at the edges. Figure 2[3] defines the study areas and extended areas and shows the transport network used and the population distribution in 2006.

It is worth noting that, although both cities tend to concentrate most of their population in the main city and peripheral towns. In Madrid, relatively few inhabitants do not have easy access to the main road axes. Barcelona has a larger quantity of populated cells that are some distance away from such axes, chiefly in areas of residential development. It is also worth pointing out that net average population densities in both study areas are similar: 3582 inhabitants/km^2 in Madrid and 3145 inhabitants/km^2 in Barcelona. However, as a consequence of the differences in urban distribution, Barcelona has a greater population density than Madrid up to a 25 km radius from the city centre. All the zones analysed in each study area are less than 40 km from the centre of Barcelona (Plaça de Catalunya) and 45 km from the centre of Madrid (Puerta del Sol).

3.3 Work specifications and computational performances

As the object of this study was to analyse the effect of variations in infrastructure performances, the weight of each destination was considered as an invariable value (2006 population). Consequently, it was the transport component that was obtained with a dynamic approach. In total, 96 scenarios were calculated on a typical mid-week day (Wednesday), which involved gathering information every 15 min on journey times from each zone to the rest. To calculate *potential accessibility*, an exponential distance-decay function was used, with a parameter of -0,065. Calibration was carried out using a modified version of the Furness algorithm [34, 35], with data from journeys for work between municipalities obtained from the 2001 Population and Housing Census in Spain [36].[4] The use of an exponential decline function avoids anomalous self-potential values [37], since it transforms all opportunities into MPUs.

Global accessibility values were obtained by adding the value of each origin zone by its weight, as expressed in the following equation:

$$A^t_{global} = \frac{\sum_{\forall i \in N} A^t_i \cdot O_i}{\sum_{\forall i \in N} O_i}; \forall t \in T \tag{E}$$

Where:

A^t_{global}	is the global accessibility weighted value of the study area, when journeys start at instant t
A^t_i	is the accessibility value (both by *average weighted impedance* and *potential accessibility* methods) of zone i when journeys start at instant t
O_i	is the weight or potential of zone i
N	is all the study zones, and T is all the instants of journeys started

The procedure was carried out on a single computer,[5] using mainly ESRI® ArcGIS10.1 GIS software. In this particular environment, the free tool for ArcGIS StreetDataProcessingTools[6] was used to create the Network Dataset, while Network Analyst tools were used to obtain different O-D impedance matrices for each of the areas and study intervals. These were calculated taking into account prohibited turns and arc directions through the analysis of hierarchical routing [38]. Hierarchical analysis considerably improves calculation times without offering solutions that are very different to those obtained from other heuristic processes installed in this environment. For the cartographic presentation of results, raster surface maps were created with IDW interpolation (specifications: power parameter = 2, with 12 points of reference).

With reference to calculation times, the most time-consuming process was the creation of the O-D impedance matrices. Each matrix took almost 19.5 min to create in the case of Madrid (Table 1), which meant 31 h to obtain the complete time series for 1 day (one matrix every 15 min, 96 scenarios). In contrast, a matrix for Barcelona was generated

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[3] The projection of all maps of this document is LAEA (EPSG:3035) and the scale is 1:500000 on DIN A-4. All of them are also available in more resolution on pdf files in Electronic supplementary material.

[4] To date of publish this paper, there are also available data of 2011 Population and Housing Census in Spain (but it was a survey). Unfortunately this data is presented very aggregated, in order to obey the statistical secret imposed by Spanish law 12/1982. As a consequence, commuter data is only available in municipalities' level, and only for municipalities with more than 80,000 inhabitants, Microdata are available too, but the results are also very aggregate.

[5] All processes were run on one computer with the following main characteristics: CPU Intel® Core™ i7-3770 CPU @ 3.40 GHz 3.40 GHz; RAM 16GB + 4GB from ReadyBoost; Operating System 64-bit Windows 8.

[6] Available for download at: http://www.arcgis.com/home/item.html?id=755f96fcde454ece8f790fecb3e031c7

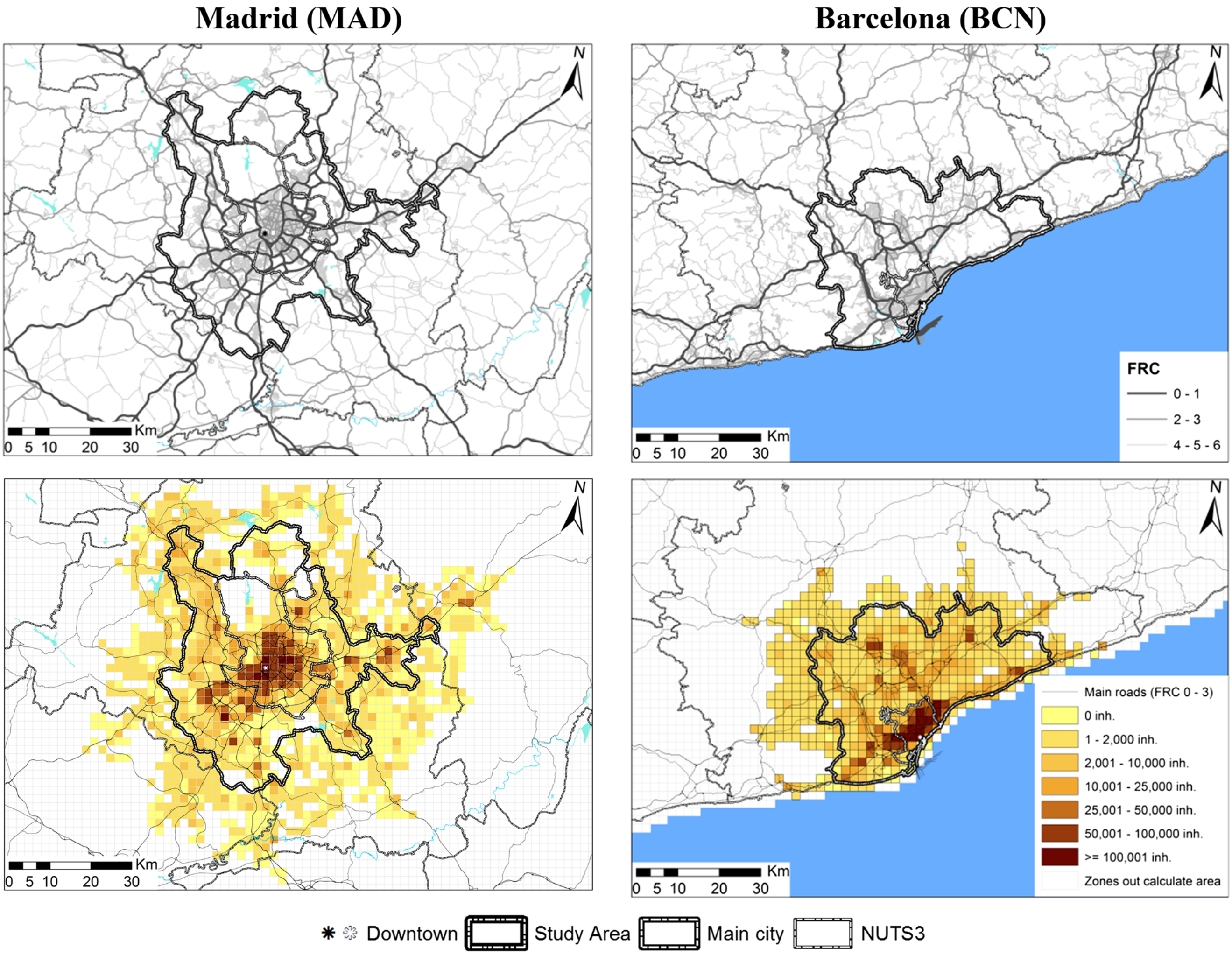


Fig. 2 Transport network, study areas, areas of calculation (with cell and population) and population distribution in 2006

in 5.7 min, which meant a total of 9 h for the 96 scenarios. The total time for the remaining processes did not exceed 30 % of the time taken to build the matrices. It is important to note that at no time were there any problems with memory.

4 Results

The results are shown in two sections. The first shows results from a global perspective and the second analyses the spatial distribution of changes in accessibility derived from the daily variation in network speeds. In addition to the maps shown in the text, several animations are available in Electronic supplementary materials which show the dynamic results more clearly.

Table 1 Summary of calculation time for the study areas

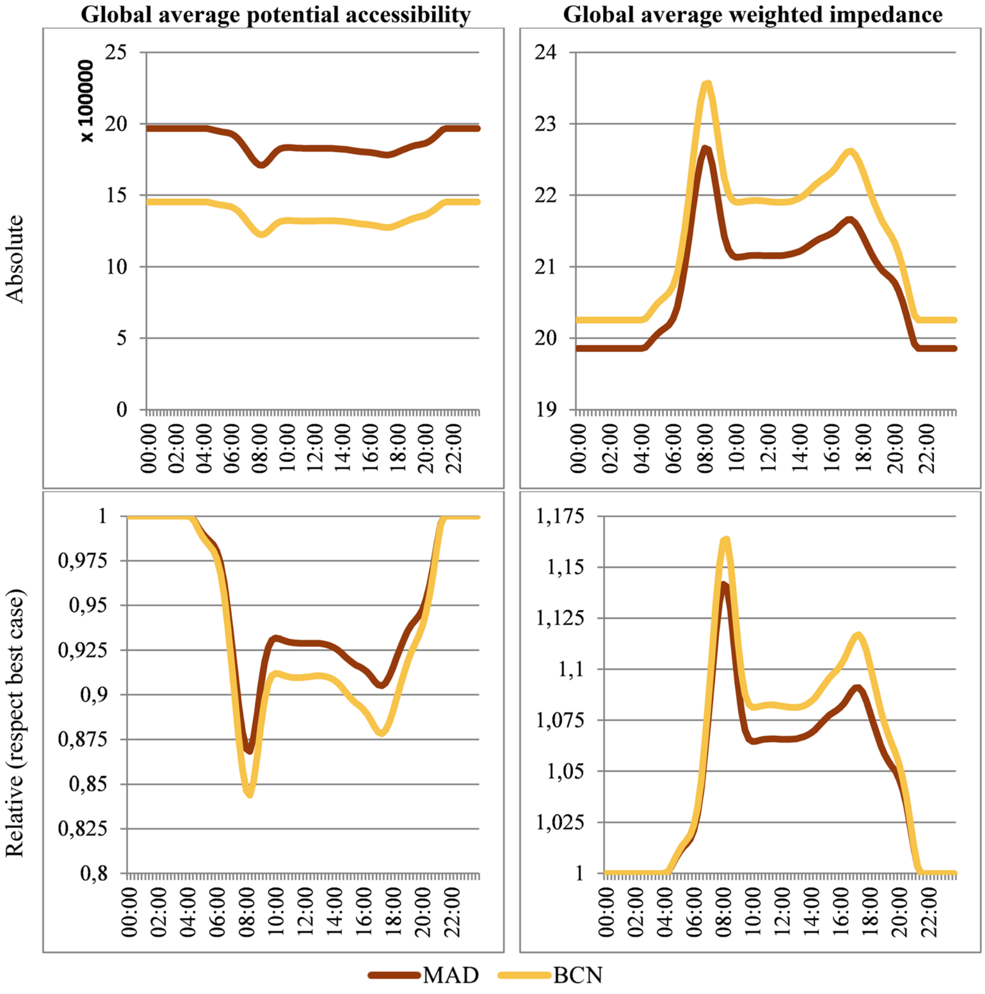
Study area	Total extended area points	Total routes	Average total routes calculation time per scenario
Madrid	1,236	1,527,696	19.40 min
Barcelona	604	364,816	5.67 min

4.1 Global results

It is interesting to see how each study area responds to changes in infrastructure performance. Figure 3 shows the temporal series for Madrid and Barcelona. In general terms, both have the same pattern, with a sharp loss of accessibility first thing in the morning. After that, for about 7 h, almost 60 % of the accessibility lost during the first peak time is recovered, until around 17:15 h, the hour of the worst case in the evening rush. After this second peak, maximum accessibility returns by 21:30 h.

However, the absolute value of potential accessibility is different in each area. On average, Madrid has 450,000 more potential market units than Barcelona. This is not surprising considering that there is a greater concentration of population in its study area. Likewise, the value of *average weighted*

Fig. 3 Temporal evolution of the global and relative accessibility value



impedance, which measures effort of access, indicates that, on average, each inhabitant of Barcelona always requires between half a minute and 1 min more than someone living in Madrid to access opportunities in that study area. In relative terms, Madrid is less affected by congestion than Barcelona. In the morning peak, the accessibility performance of Madrid is 86.98 % of its global potential accessibility value in relation to the free flow situation; it is caused by an increment of 14.15 % in its global weighted impedance. For Barcelona, these values are 84.38 and 16.37 % respectively. Between peaks, values are stable in global potential accessibility around 92 % in Madrid and 90 % in Barcelona respect free flow situation, and during afternoon peak, at 17:15, these values drop to 90.85 and 87.91 % respectively.

4.2 Daily spatial accessibility distribution

Changes in road performance due to traffic congestion do not have a uniform impact on the study areas. As Fig. 4 and the supplementary electronic material animations show, using the average weighted travel time (which makes it possible to compare both cities in absolute values). Central areas have less average impedance for reaching opportunities. In the case of Madrid, the resulting contours are concentric, while in Barcelona the area with high accessibility values includes the main city and part of the system of peripheral towns situated around an inland axis parallel to the coast, known as the Mediterranean corridor: AP-7 | E-15 motorway. In both cases, the distribution of zones with greater and lesser accessibility is maintained throughout the day. It should also be noted that, as expected, the effects of congestion begin in the more peripheral zones that are at some distance from a main road. In the same way, the lowest global accessibility values do not correspond with the minimum values in these more distant zones, this is experienced some minutes earlier.

The rest of the results use relative values obtained from potential accessibility. Figure 5 shows the maximum impact of congestion, i.e. the ratio between the minimum and maximum accessibility recorded in each zone. It also shows the total time that each zone is below its average potential accessibility (amount of time affected by low network performance).

Location, relationships with neighbours zones and each zone's own opportunities inside itself, also known as self-

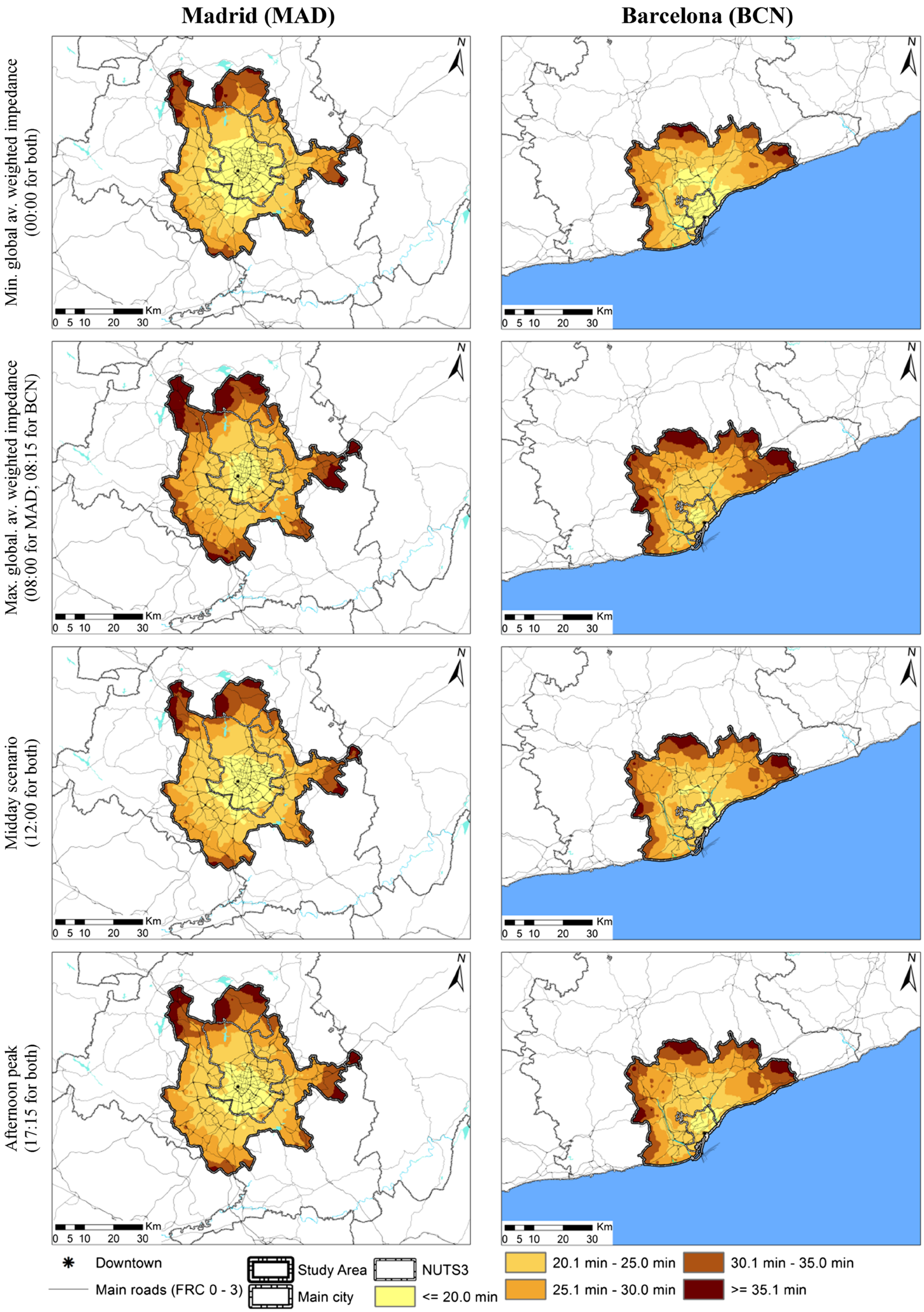


Fig. 4 Comparing accessibilities at different times of day

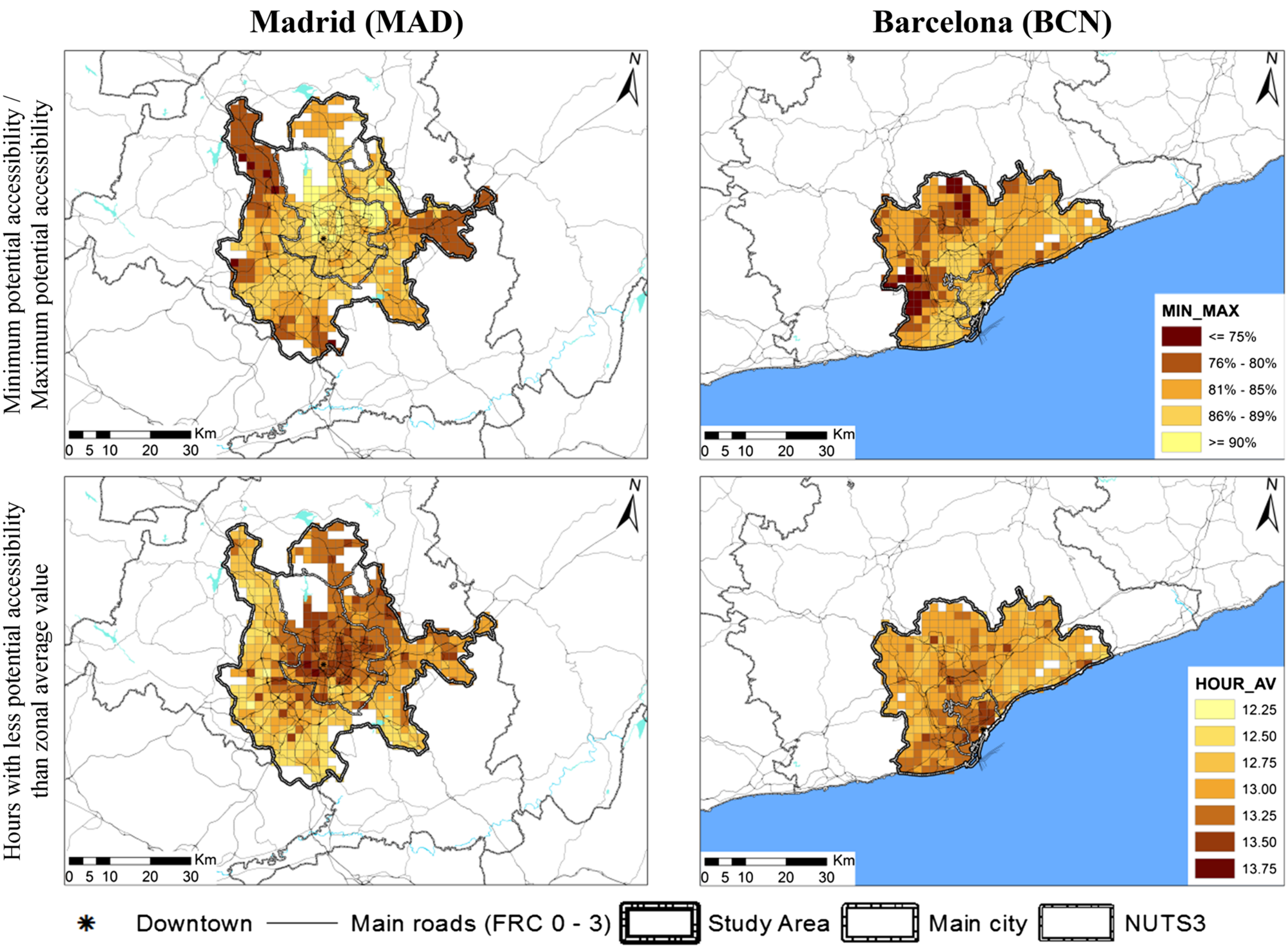


Fig. 5 Potential accessibility behaviour patterns

potentials, are essential elements for understanding how temporal changes in network speed affect the spatial accessibility distribution. As Fig. 5 shows, each study area behaves differently. Madrid has a large centre with fewer reductions in MPUs between the worst and best recorded situations. The central area also includes the north-central and south-central zones. The zones that experience fewer hours below the average accessibility value are the southern metropolitan areas, being the most congestion-resilient ones. However, in the north-western metropolitan area (along the A-6 motorway corridor), accessibility is reduced by almost 25 % at the worst times. Nevertheless, the total number of hours below the average value is low (less than 13). In the north, along the A-1 corridor, the situation is the opposite, with little loss at the peak of worst accessibility but a high number of hours below average value. The zones most negatively affected by congestion in the metropolitan area of Madrid are in the eastern corridor (A-2) with significant reductions between maximum and minimum accessibility values and below average accessibility during much of the day.

Unlike Madrid, Barcelona has greater variability in its accessibility distribution. The zones with the least variation between maximum and minimum values are situated in the centre, south-west and north of the main city. However, for most of the day, these zones suffer from values that are lower than their average accessibility. The remaining zones are more affected by peak congestion as they experience greater reductions in accessibility. It is worth noting that part of the so-called "second metropolitan ring of Barcelona" [7] behaves in a similar fashion to the centre of the city, but with more marked peak reductions in accessibility but few hours below their average values.

Knowing at what time of the day each zone has its lowest potential accessibility value (Fig. 6) is of great use for explaining the dynamics of the effects of temporal variation in accessibility. Both cities show the same pattern, with the

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[7] Main cities: Granollers, Mataró, Sabadell and Terrassa.

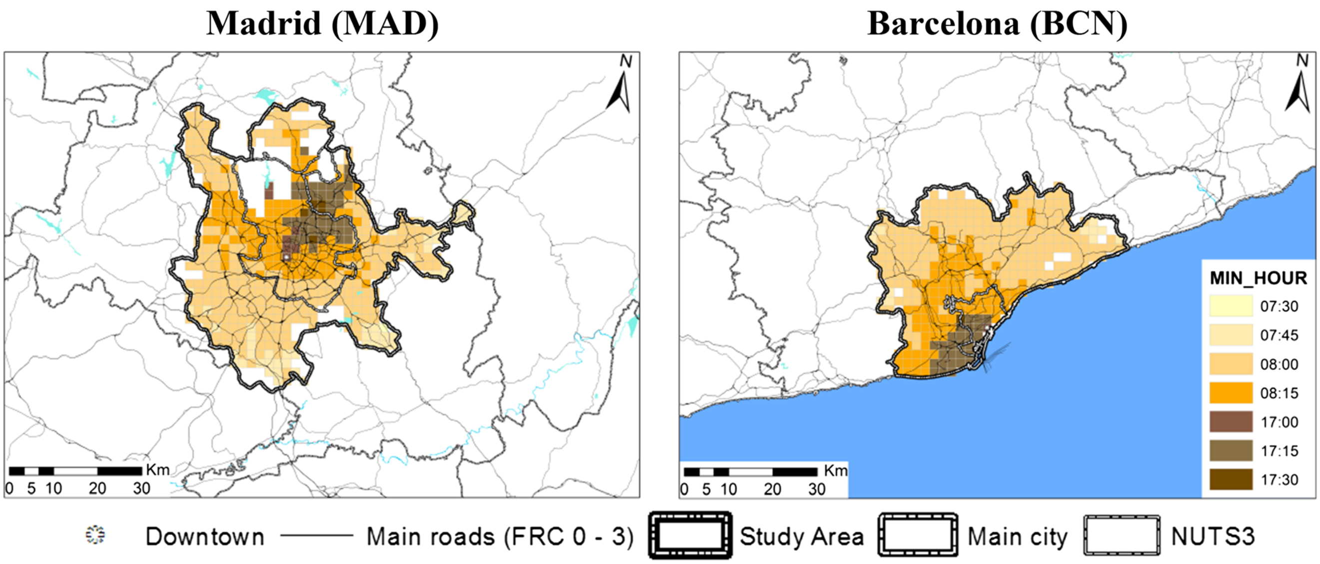

Fig. 6 Time with lowest MPUs

worst level of accessibility in almost all the study area occurring during the morning, and with an outside-to-inside pattern. However, some zones around the historic centres of the main cities experience their worst congestion during the late afternoon/evening peak. These areas include the centres of the main cities, airports, and a large part of the business parks.

5 Conclusions and future research

The aim of this article is to capture the temporal variation of infrastructure performances in measurements of accessibility. Until now, the lack of reliable data and computational limitations has become obstacles to any in-depth analysis of dynamic phenomena, such as daily accessibility. The starting point of this challenge has been information on road infrastructure performance from the years 2011 and 2012, obtained from observations recorded by thousands of users of GPS navigators [39].[8] By measuring accessibility with real observed speeds, it is possible to broaden our understanding beyond simply knowing where and when congestion takes place, i.e. at arc level. Also, it will be possible to start answering some questions at origin trips zone or inhabitant level, such as whom it affects, when and how long it affects them, what is the magnitude of these impacts, and, perhaps most importantly, why they are affected.

The article shows how to introduce dynamic impedances in two traditional accessibility measurements using a current ordinary personal computer. Although computational costs are not too high for a single scenario, they can be a factor in determining the temporal interval to use for calculating a complete temporal series. For the purposes of this article, we therefore opted to work with 15-min intervals instead of the 5 min that were originally envisaged. Apparently, this option did not result in any significant loss in detail of the results. However, new techniques as cloud computing can offer us enough resources to easily lead the limits observed on this study with a single computer and get deeper knowledge in dynamic accessibility studies.

The areas of study, Madrid and Barcelona, show similar patterns in the variation of global accessibility, measuring as reachable population, throughout the day. Respecting the spatial distribution of the effects of congestion, each area shows a different result due to the morphology of its respective metropolitan region. In any case, it seems that systems based on strong concentration of opportunities make accessibility more resistant to congestion, as Levine and Garb suggest [40]. This is partly because zones with lower population, and therefore less self-potential, are more dependent on the potential of the other zones and the transport component. Another result worthy of mention is that centres of activity or of economic importance, which experience their worst accessibility in the late afternoon, can easily be identified.

Other variables that exist have not been explicitly included in this article and these variables may explain some of the results obtained. For example, the provision of public transport services may encourage people not to use their private vehicles and therefore not reduce network performances, and their effects are implicitly included on observed speed used on this paper. In-depth analysis of this information is essential in any attempt to avoid the unwanted effects of congestion. Dynamic measurements also imply an important step forward in the search for the elusive but unmistakable relationship between accessibility and mobility that has generated so many scientific discussions [41]. Future research should tackle to find this relationship, as well as how congestion can trigger some reaction

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[8] TomTom has also some internal nonpublic reports about this data. If you want more information, please contact TomTom.

on housing or location. They must also include methodologies to efficiently compare different solutions/scenarios.

The present study has focused on origins, which is interesting from the point of view of location policies involving zones that generate journeys (active accessibility), such as new residential developments, zones of denser growth or logistic urban micro-platforms. The same process can also be used for destinations (passive accessibility) to find locations that are resilient to the congestion of services like medical centres and schools. This is of particular interest in public venues that are accessed mainly by road, and it may also be interesting in future research on territorial/social policy

Using only the population data as opportunity values may be very arguable in some accessibility studies, especially in metropolitan contexts, where the specialization of land use has an important role. Nonetheless, it is worth mentioning each study requires using any good methodology and adequate and available data according to its aims. Moreover, in comparison studies it is really important to get results without biases, e.g. using the very same methodology to get original data or standardizing data. Unfortunately, the only available trustworthy data, for the study areas at 1 km^2 grid level, is population data. In fact, some other socio-economic data available on this detailed level have been generate as function of population [42]. In our case, access to population can be interesting to show a large number of effects of congestion on the territorial accessibility. Using other type of opportunities should be used to expand the knowledge of this phenomenon and its consequences in other study scope in future research.

As a final comment, it should be pointed out that explaining the consequences of dynamic effects on static maps entails significant difficulties owing to the incorporation of the temporal component. Although the best way of representing this appears to be through animations, it would be interesting to reinvent some static maps that could also capture this information and guarantee the soundness and plainness of the indicators used. This is no trivial aspect as decisions on various actions may depend on it.

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References

1. Martens MJ, van Griethuysen S (2007) The ABC location policy in the Netherlands. TNO Inro Report
2. Department of Environment, Department of Transport (1994) Planning policy guidance: transport (PPG13). http://www.illo.demon.co.uk/ppg13.htm. Accessed 14 Jan 2014
3. European Commission (1999) European spatial development perspective. European Communities, Luxembourg
4. Geurs KT, van Wee B (2004) Accessibility evaluation of land-use and transport strategies: review and research directions. J Transp Geogr 12:127–140. doi:10.1016/j.jtrangeo.2003.10.005
5. Hodge DC (1997) Accessibility-related issues. J Transp Geogr 5: 33–34. doi:10.1016/S0966-6923(96)00050-6
6. Morris JM, Dumble PL, Wigan MR (1979) Accessibility indicators for transport planning. Transp Res A Gen 13:91–109. doi:10.1016/0191-2607(79)90012-8
7. Bruinsma F, Rietveld P (1998) The accessibility of European cities: theoretical framework and comparison of approaches. Environ Plan A 30:499–521. doi:10.1068/a300499
8. Breheny MJ (1978) The measurement of spatial opportunity in strategic planning. Reg Stud 12:463–479. doi:10.1080/09595237800185401
9. Hansen WG (1959) How accessibility shapes land use. J Am Inst Plann 25:73–76. doi:10.1080/01944365908978307
10. Schürmann C, Talaat A (2000) Towards a European peripherality index. Report for General Directorate XVI Regional Policy of the European Commision. Institut für Raumplanung. Universität Dortmund. Dortmund (Germany)
11. Gutiérrez J, Condeço-Melhorado A, López E, Monzón A (2011) Evaluating the European added value of TEN-T projects: a methodological proposal based on spatial spillovers, accessibility and GIS. J Transp Geogr 19:840–850. doi:10.1016/j.jtrangeo.2010.10.011
12. Vandenbulcke G, Steenberghen T, Thomas I (2009) Mapping accessibility in Belgium: a tool for land-use and transport planning? J Transp Geogr 17:39–53. doi:10.1016/j.jtrangeo.2008.04.008
13. Quiroga CA (2000) Performance measures and data requirements for congestion management systems. Transp Res C Emerg Technol 8:287–306. doi:10.1016/S0968-090X(00)00008-5
14. Braess D, Nagurney A, Wakolbinger T (2005) On a paradox of traffic planning. Transp Sci 39:446–450. doi:10.1287/trsc.1050.0127
15. Braess D (1968) Über ein Paradoxon aus der Verkehrsplanung. Unternehmensforschung 12:258–268
16. Gutiérrez J (2001) Location, economic potential and daily accessibility: an analysis of the accessibility impact of the high-speed line Madrid–Barcelona–French border. J Transp Geogr 9:229–242. doi:10.1016/S0966-6923(01)00017-5
17. Geurs KT, Ritsema van Eck J (2001) Accessibility measures: review and applications. Evaluation of accessibility impacts of land-use transportation scenarios, and related social and economic impact. RIVM report 408505 006. Bilthoven (Netherlands)
18. Reggiani A (1999) Accessibility, trade and location behaviour. Ashgate Publishing Limited, Aldershot
19. Handy SL, Niemeier DA (1997) Measuring accessibility: an exploration of issues and alternatives. Environ Plan A 29:1175–1194. doi:10.1068/a291175
20. Curl A, Nelson JD, Anable J (2011) Does Accessibility Planning address what matters? A review of current practice and practitioner perspectives. Res Transp Bus Manag 2:3–11. doi:10.1016/j.rtbm.2011.07.001
21. Páez A, Scott DM, Morency C (2012) Measuring accessibility: positive and normative implementations of various accessibility indicators. J Transp Geogr 25:141–153. doi:10.1016/j.jtrangeo.2012.03.016

22. Bertolini L, le Clercq F, Kapoen L (2005) Sustainable accessibility: a conceptual framework to integrate transport and land use plan-making. Two test-applications in the Netherlands and a reflection on the way forward. Transp Policy 12:207–220. doi:10.1016/j.tranpol.2005.01.006
23. Gutiérrez J, Urbano P (1996) Accessibility in the European Union: the impact of the trans-European road network. J Transp Geogr 4:15–25. doi:10.1016/0966-6923(95)00042-9
24. Ben-Akiva M (1985) Dynamic network equilibrium research. Transp Res A Gen 19:429–431. doi:10.1016/0191-2607(85)90042-1
25. Chiu Y-C, Bottom J, Mahut M et al. (2011) Dynamic traffic assignment. A Premier. Transport Research Circular E-C153. Washington, DC (USA)
26. Wu Y-H, Miller HJ, Hung M-C (2001) A GIS-based decision support system for analysis of route choice in congested urban road networks. J Geogr Syst 3:3–24. doi:10.1007/PL00011466
27. Dijkstra EW (1959) A note on two problems in connexion with graphs. Numer Math 1:269–271. doi:10.1007/BF01386390
28. Chabini I (1998) Discrete dynamic shortest path problems in transportation applications: complexity and algorithms with optimal Run time. Transp Res Rec 1645:170–175. doi:10.3141/1645-21
29. Dean B (2004) Shortest paths in FIFO time-dependent networks: theory and algorithms. Rapport technique, Massachusetts Institute of Technology. Boston (USA)
30. Eurostat (2011) Local Administrative Units (LAU). http://epp.eurostat.ec.europa.eu/portal/page/portal/nuts_nomenclature/local_administrative_units. Accessed 20 Jan 2014
31. European Environment Agency (2007) EEA reference grids. Permalink to this version: 9B755D9F-8B6B-4CE0-9270-0963E10B2FC8. Accessed 20 Jan 2014
32. Eurostat (2006) Population Distribution - Demography. http://epp.eurostat.ec.europa.eu/portal/page/portal/gisco_Geographical_information_maps/popups/references/population_distribution_demography. Accessed 20 Jan 2014
33. ESPON (2014) ESPON 2013 Database Dictionary of Spatial Unites. http://database.espon.eu/db2/jsf/DicoSpatialUnits/DicoSpatialUnits_onehtml/index.html. Accessed 20 Jan 2014
34. Furness KP (1965) Time function iteration. Traffic Eng Control 7:458–460
35. Ortúzar JD, Willumsen LG (2011) Modelling transport, 4th edn. John Wiley & Sons, West Sussex
36. INE (2004) Population and Housing Census 2001. http://www.ine.es/en/censo2001/index_en.html. Accessed 10 Dec 2013
37. Frost ME, Spence NA (1995) The rediscovery of accessibility and economic potential: the critical issue of self-potential. Environ Plan A 27:1833–1848. doi:10.1068/a271833
38. ESRI (2014) About network analysis with hierarchy. http://resources.arcgis.com/en/help/main/10.1/index.html#//004700000057000000.LastaccessedonJanuary21. Accessed 25 Feb 2014
39. TomTom (2013) Speed profiles. http://www.tomtom.com/en_gb/licensing/products/traffic/historical-traffic/speed-profiles/#tab:tab1. Accessed 20 Jan 2014
40. Levine J, Garb Y (2002) Congestion pricing's conditional promise: promotion of accessibility or mobility? Transp Policy 9:179–188. doi:10.1016/S0967-070X(02)00007-0
41. Handy S (2005) Smart growth and the transportation-land use connection: what does the research tell us? Int Reg Sci Rev 28:146–167. doi:10.1177/0160017604273626
42. Milego R, Ramos MJ (2013) Disaggregation of socioeconomic data into a regular grid and combination with other types of data. Technical Report ESPON