The impact of urban road congestion on territorial accessibility in the largest Spanish urban zones

Borja Moya-Gómez
Ph.D. Research; Transport, Infrastructure and Territory Research Group (t-GIS), Complutense University of Madrid; Spain
Juan Carlos García Palomares
Assistant Professor; Transport, Infrastructure and Territory Research Group (t-GIS), Complutense University of Madrid; Spain

ABSTRACT
Road congestion is one of the most common daily problems in large urban zones. Their effects are considered an inefficiency of the transports – land use – people system. Previous attempts to fix this problem tend to fail since they are usually transport-based, because of the results of the interrelationships facets of system studies are blurry and their data could not be enough to get into issue. Nowadays, we can set over those limits now that the new ITs allows us to catch big data from reality (traffic, individual behavior, economic flows…). In this paper, we are interested in knowing how congestion can change the territorial accessibility values for the largest urban zones in Spain during whole regular weekdays, by using TomTom® historical Speed Profile data and GIS software (ESRI® ArcGIS). Our results seem to show that the interaction between land use and transport network is a fundamental piece to understand congestion. Despite the identical main morning peak in both areas and space-time distribution of congestion, the evolution of affected population per times shows that Madrid more congestion resilient than Barcelona.

Keywords: congestion, territorial accessibility, transports - land use - people system, big data, global navigation satellite system data, GIS.

1. INTRODUCTION

Peoples' dependence on the transport systems has been growing in the last several decades. Nowadays, we cannot satisfy some necessities without using any transport. For instance, we import many goods from far countries or we do not live physically close to our jobs or study places. But, paradoxically, traveling is rarely a desired activity; since we would like to avoid it, making any trip or receiving any goods immediately and instantly. Our life style is strongly transport-based and any malfunction on the transport network affects us. Societies want to understand why those incidents occur and try to prevent them, given that their consequences may be unacceptable. One of the most common problems might be congestion, especially in urban zones.

Congestion occurs when demand levels approach the capacity of a facility (Ortúzar and Willumsen 2001, p.7). Moreover, capacity may also be temporally reduced because of accidents, works on network or weather conditions. Congestion effects are shown as a reduction of levels of service offered and an increment of the travel time respect any non-congested state. Besides, congestion introduces instabilities and makes the transport network more vulnerable or less resilient; it reduces the capacity to confront successfully an unexpected incident and it increments the time/cycles needed to recover normality.

The congestion costs in the large cities are well known. In 2011, each commuter of main US cities wasted 38 hours and 19 gallons (72 liters) of fuel in congestion, and total congestion costs sum up to $818 per traveler (Schrank et al., 2012). For the biggest cities of Europe, the total delay per year for trip of 30 minutes came to 97 hours for Paris and Rome, 89 h for Milano, 84 h for London, 78 h for Hamburg, 74 h for Berlin, 65 h for Barcelona and 59 h for Madrid (TomTom®, 2013). In global for all European Union, total congestion cost was estimated in 1% of GDP (Christidis and Ibáñez Rivas 2012). In addition, congestion increases negative externalities such as accidents, noise and pollution, it reduces the life of vehicles (Schallaböck and Petersen, 1998), and it has an impact on the quality of services and performance of road transits as well.

For growing cities, urban congestion may be a significant obstacle for large urban development and their economies, since their problems may be bigger than the benefits of the economies of scale in agglomerations (Batty, 2008). Likewise, Gospodini (2002) and Turok and Mykhnenko (2007) uphold that small cities are settling over all Europe, since they do not have congestion problems. The concept of city includes high population and activities density values.

Congestion has network effects as well. On the one hand, the congestion state can move upstream. Considering that any road’s edge can be defined as a waiting system; when a road is congested (acting as an occupied server), it makes lines on neighbor upstream roads, reducing temporally their capacities and levels of service and, thus, extending (pre)congestion state through the network. It is known as spillback effects (Daganzo, 1999). On the other hand, congestion of infrastructures also changes route choice and neighbor regions, it is known as spillover effect. The congestion of particular regions can make other regions less attractive to some activities despite their transports well-functioning network. It may also increase social inequalities due to increase complexity to reach opportunities. Moreover, distant regions may show congestion because drivers change their routes to avoid the congestion in some downstream downtown roads. We must not forget that congestion is a temporal incident too; since gridlocks can appear and disappear during time study.

One of the most common traditional visions to fix congestion effects is only acting on transport (as known as mobility) component, e.g. enlarging the road network. Nevertheless, it usually fails and it tends to harm the performance of other modes of transport, and to affect land uses, societies and their relationships (Litman, 2013). On the other hand, also alters ecosystems: for instance, if we remove a road network bottleneck (which might be a really expensive action), it may foster more traffic and, as a consequence, it may increase parking problems, it may reestablish the congestion state and it even may extend the instability over the network. Not taking into account the interaction between land use, transport network, individual behavior and their temporal variations of behavior or performance is a cause of this failure. Therefore, congestion has become not only in a transport (or network) problem but also transport – land use – people system problem. Hereto good solutions have to regard the system facets or, at least, some simplification. Accessibility values may be useful tools to understand, predict and solve the congestion problems because they can incorporate all these facets.

On the present paper, we study the impact of the urban road congestion on territorial accessibility in two Spanish urban zones (Madrid and Barcelona) by using big data from historical Speed Profiles of TomTom® and GIS software. Our results identify what zones show worst resistance of congestion, why they are affected, and provide us some guidelines to understand how policies and specific actions may be needed to eliminate the unwanted consequences of this phenomenon.

This paper is structured as follows. In section 2, a brief review of accessibility and congestion, and previous studies. In section 3, we introduce a methodology to study accessibility with congestion and which is used in this paper. Section 4 introduces the studies areas, the specifications as well as the result of our studies. Finally, in the last section, we discuss about conclusions and possible next steps and future research.

2. ACCESSIBILITY AND CONGESTION. THE APPROACHES METHODS

The accessibility concept is widely used in literature, and it is increasingly used in transport-land use decisions. It measures the performance of transport network in human activities system and their consequences, such as in individual behavior, in land pricing or in firms' location. It is also used to understand how any policy and/or specific action may modify human activities and it is the basis of land use planning policies such as ABC location policy of the Netherlands (Martens et al., 2000). Unfortunately, this concept is difficult to synthesize, thus it does not have a unique definition neither a unique method to quantify.

In spite of straightforward definitions of accessibility, such as *Accessibility reflects the extent to which the transport-land system enables (groups of) individuals or goods to reach activities or destinations by means of a (combination of) transport(s) mode(s)* (Geurs and Ritsema van Eck, 2001), all definitions underlie the complexity of transport - land use - people system and its temporal variations. We should use the definition of accessibility concept and a form to calculate it depending on each situation, the data available, and so on (Gutiérrez, 2001).

2.1. Static accessibility with congestion approaches

To face the problem of system complexity, we have to deal some with constants characteristics, under equality hypothesis of some of their components or simplify the range of their interrelationships. For instance, those studies that use the basic potential accessibility (Hansen, 1959), as shows in equation (1) for origins, measure accessibility for regions considering invariable travel costs for each edge of network during every trip, individual characteristics uniform (gender, education, income, car-owing, schedules, and so on) and to avoid competition effects. Because of simplification of their edge costs, they can be called static accessibility studies.

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

Subject to: (1)

$$c_{ij} = \sum_{e \in E} \alpha_{eij} \cdot c_e;\ \forall\, ij \in G$$

Where: A_i is accessibility value in zone i; D_j is potential of zone j; $f(c_{ij})$ is the cost-decay function; c_{ij} is cost of travel from zone i to zone j, it is predefined and constant; α_{eij} is binary variable which indicates if the edge e is used by travel from zone i to zone j; c_e is cost of edge e, it is predefined and constant; N is the set of zones in study region; G is the set of travels between each zone in study region; and E is the set of edges in study network graph. We can study accessibility on destination with same equation as well.

A significant advantage of static studies is that the data requirements are often easy to find in developed countries. We only need information about potential of destinations, e.g. population, and determinate a fixed travel cost for each origin-destination pair.

Static studies fields are usually limited to compare accessibility between regions. They might be used to study accessibility values among different static situations and understand the effects of a specific policy or action as well. Therefore, those studies can compare different real temporal situations, or current and forecasted scenarios; the last ones are obtained by foreseeable mishaps or programmed improvements on study network, or changing uses on land.

It is worth mentioning that static accessibility studies consider that the network costs are known and invariable per each studied situation; e.g. if we study differences between off-peak hour and peak hour with statics, we will have a unique weighted cost network per scenario. Although static methods can compare accessibility among different temporal situations, and, consequently, congestion effects could be studied by those methods. Their results cannot catch all temporal variations of performance of the network effects, so they may not be adequate for going deeper into congestion issues. Nevertheless, statics may sometimes work well as an approximation of the time-space framework.

2.2. Dynamic accessibility with congestion approaches

As presented in the previous section, congestion is a spatial-temporal effect. Thus the travel cost of edges varies while a study virtual mobile is traveling over the network; e.g. if two technically identical vehicles with different origin and destination, starting their trip at the same time, have to use a same edge at different time. The cost to use that edge depends on when each mobile need to use it and its cost may be different. Dynamic accessibility studies include this network behavior.

Using dynamic methods entail higher computational costs than statics. The network performance changes during study time (more required data than statics) can affect on route choice. Dynamic shortest route is not usually defined as traditional Dijkstra's algorithm route, since it is not necessarily created by the sum of the shortest edges between each origin-destination path. Unlike statics, dynamic shortest route may require using some sets of expensive edges at certain instant in order to economize on the total cost route. Finally, heuristic dynamic shortest routes algorithms only tend to obtain suboptimal solutions.

2.3. Working with congestion

A significant challenge of accessibility studies with congestion, both dynamics and statics, is to obtain a real weighted cost network or any information about performances of the network per interval of study. Given that traditional surveys cannot capture correctly this information and traffic counting data usually only refers to main roads. For future scenarios, that information can only be simulated. For currents or historical, they may also be estimated by simulations (Wu et al., 2001) or we may try to catch time-based information from users who accept to share theirs cellphone and navigator tracks (Quiroga, 2000; Sia et al., 2009). The main companies of navigators systems, such as TomTom®, sell these datasets. Anyway, those datasets may be gigantic, expensive or they may not be accessible for urban networks as a whole.

Due to the complexity of accessibility calculation incorporating infrastructure congestion and the difficulty to obtain correct data, previous studies are almost restricted to non-individual based method, small areas and a selected opportunities. Many studies of accessibility with congestion have been measured by time series of contour measures based, which are a simplification of basic potential accessibility using a dummy variable as value of cost function (1 if the destination is inside cost threshold, otherwise 0). It has been used for both local studies (Casas, 2003; Lei and Church, 2010; Møller et al., 2012) and regional (Bertolini et al. 2005). Nevertheless, congestion has been studying as a transport problem, some of these accessibility studies are infrastructure-based (omitting any relationship with land use and people), e.g. average speeds, average level of service experimented, or travel time between each origin and destination, such as Vandenbulcke et al. (2009) did with two theoretical speeds static scenarios.

An alternative way to introduce the time variation of infrastructure performance on accessibility measures consists in individual based methods, such as space-time prisms and their potential path areas (Lenntrop, 1976; cited in Miller, 1991, and Neutens et al., 2011). Notwithstanding, those methods seem more adequate to undertake whole accessibility studies (transport – land use – person – time), since they explicitly incorporate time dimension and individuals characteristics, such as gender, age, incomes, car-owing, schedules, and so on. Their data necessities are extremely huge, and are basically focused on person behavior, thus congestion effects tend to be in the background. Hitherto, there are a few accessibility studies with congestion which uses space-time prisms, such as Weber and Kwan (2002).

3. TERRITORIAL ACCESSIBILITY WITH CONGESTION: THE METHODOLOGY

The main purpose of this paper is to understand how congestion may change territorial accessibility values. We need to use methods that can clearly show these magnitudes. In the same way, it has to be computationally feasible and the results must be as easily understanding as possible. The basic potential accessibility measure (eq. 1) can be adequate for our aims if only we add the temporal variation of travel costs, which depend on performance of the network's edge at the moment when it has to be used, as show in equation 2.

$$A_i^t = \sum_{j \in N} D_j \cdot f\left(c_{ij}^t\right); \; \forall \, i \in N, \; t \in T$$

Subject to:

$$c_{ij}^t = \sum_{m \in M} \sum_{e \in E} \alpha_{eij}^{tm} \cdot c_e^m \; ; \; \forall \, ij \in G, t \in T \qquad (2)$$

Where: A_i^t is accessibility value in zone *i* and starting travel at time *t; D_j* is potential of zone *j*; $f\left(c_{ij}^t\right)$ is the cost-decay function; c_{ij}^t is expected real least cost of travel from zone *i* to zone *j*, and starting travel at time *t*; α_{eij}^{tm} is binary variable which indicates if the edge *e*, starting its use at time *m*, is used by travel from zone *i* to zone *j*, starting travel at time *t*;c_e^m is expected real cost of edge *e*, starting its use at time *m*; *N* is the set of zones in study region; *T* is the set of starting travel time; *G* is the set of travels between each zone in study region; *E* is the set of edges in study network graph; *M* is the set of intervals in study time.

Note that we use constant values for the potential of zone *j*, which allows us to catch only congestion effects and not to be interfered by others actors of accessibility time variations, such as schedules of workplaces. Besides, for daily studies, population and GDP of zone *j* may be considered invariable during whole study time. Equation 2 implies to accept that we work in aggregate scale (zones), without individual differences, or competition effects between zones as well.

An important issue of potential accessibility measures to be considered is the self-potential problem (Frost and Spence, 1995), which means the accessibility value for each zone *i* depends on all but potential of this zone *i*. Some methods to prevent this consider enough internal cost, which must be added to travel cost between zone and to internal cost of destination, especially in negative-exponent power function, using exponential-family functions, calibrating a piecewise-defined (at least) continuous function.

As a result, we have a set of accessibility values, as temporal intervals. They show how the accessibility changes during study time, for each zone of our study region. The accessibility studies may be broadened with temporal series analysis. We are interested on describing these temporal changes on geographical context, to identify what zones are most vulnerable to congestion and the reasons behind or how many people are affected by a determined level of congestion. Moreover, a whole region temporal variation of accessibility value can be estimated.

The total relative accessibility weighted by population for each interval ($Glob.Rel.A^t$), as a global study area indicator, is shown on Equation 3: A_i^t is accessibility value in zone *i* and starting travel at time *t*, pob_i is the population of zone *i*, *N* is the set of zones in study region, and *T* is the set of starting travel time. The numerator of equation 3 is the global average accessibility value for instant *t* ($Rel.A^t$), while denominator can be understood as accessibility value without congestion effects.

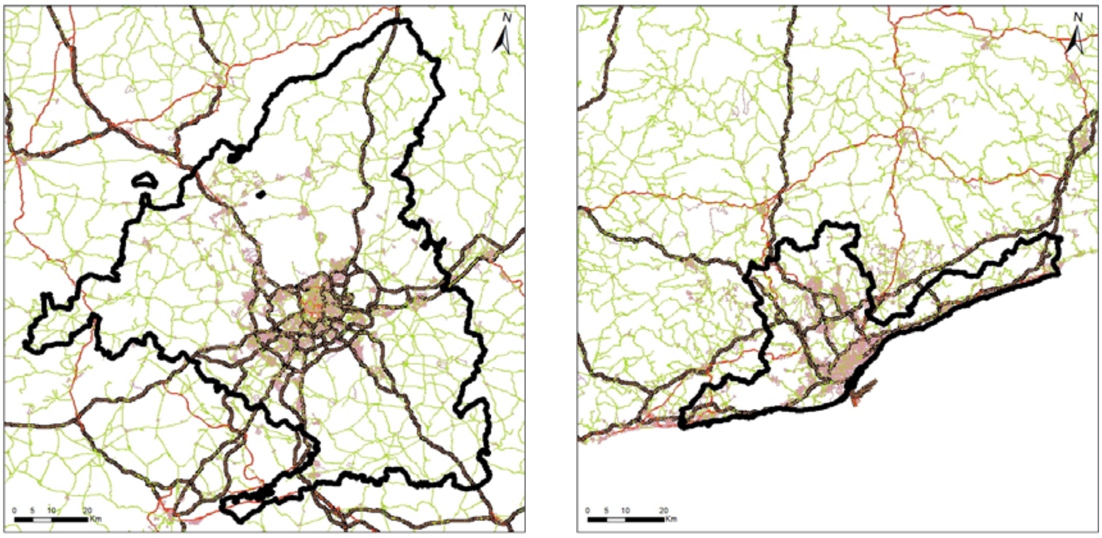
$$Glob.Rel.A^t = \frac{\frac{\sum_{i \in N} A_i^t \cdot pob_i}{\sum_{i \in N} \cdot pob_i}}{max\left(\frac{\sum_{i \in N} A_i^t \cdot pob_i}{\sum_{i \in N} \cdot pob_i}\right)} \; ; \; \forall \; t \; \in T \qquad (3)$$

4. CASES OF STUDY: CONGESTION ON THE SPANISH LARGEST URBAN ZONES

Our case study areas are of the Large Urban Zones (LUZ), version 2010, of Madrid and Barcelona (Spain). The European Environment Agency (EEA) in the Urban Atlas defines these regions (EEA, 2010). Despite in this paper we only shown two cities, our main proposal is study the main urban areas of Europe, and therefore we chose to use LUZ because it may represent a common definition for all European urban areas.

The population of LUZ Madrid is 6,006,966 inhabitants / 8,469km^2; for Barcelona these values are 4,445,282 inhabitants / 2,019km^2, where population data are from aggregate 4km^2 squares contain in each LUZ (Eurostat, 2009). The municipality of Madrid represents 52.29% of the population of LUZ and its area represents 7.14%, while Barcelona is 34.36% of the total population and its area is 5.04%. Both areas have proximately 80% of their population within 20km circle centered on city centers. Study LUZs are shown in

Figure 1.



LUZ Madrid LUZ Barcelona

Figure 1: Main road network and urban system of study LUZs

4.1. Data and specifications

In this paper, we used the network provided by TomTom® (Version March 2013). The dataset includes the whole Spanish road network, and the Historical Speed Profile of biggest traffic roads. Every edge belongs to a Functional Road Class or FRC. The network which include parking access, pedestrian streets, neighborhood streets, rural roads) are 73.59% total network. Those roads have barely enough traffic to get any speed profile. Only 0.97% these roads have one. To simplify network, we decided to omit FRC7 and FRC8 roads without losing significant precision and network connectivity on our study. The rest of the network has 46.77% edges with speed profile.

Each edge with Speed Profile may be referred to 7 predefined profiles, one per day, or to 5 profiles, one per weekday. There are 98 predefined profiles which show the variation of in percentage speed respect free flow speed during the day in intervals of 5 minutes; i.e. two different edge, such as a highway edge and urban edge, may have same profile for Wednesdays, but their expected speed is different since their free flow speed are different. This data structure save memory and computational costs, and it is adapted to be used on ESRI© ArcGIS. There are not any speeds profiles that have less speed than free flow speed outside of the interval between 04:30 and 21:20, both times included.

We considered Wednesdays as the typical weekday, thus that day is the farther any weekend day or to/from weekend and their travel patterns. We limited to 90 min the maximum travel time for any route as well. Hence, we calculated 75 cost routes sets for each zone to catch all daily temporal variations, one per every 15 minutes between 03:00 to 21:30, both times included. The used cost decay function is exponential travel time-based, calibrated by working commuter travels and population datasets of last published census of

INE (INE, 2004) and modified travel time from TomTom® data. Its coefficient is -0.065.

We used to determine the origin and destination points the centroids of $4km^2$ square zones, which was created by aggregation of $1km^2$ EEA reference grid (EEA, 2009). The used grid allows us to guarantee precision and affordable computation costs. Moreover, to eliminate possible delimitation effects, we added out-LUZ zones within 30min for free flow speed on network; summing up to 4,314 reachable studies zones for Madrid and 1,637 for Barcelona. For each cell grid (acting as zone), we have the total population data from GISCO – Eurostat (Eurostat, 2009), which was used as potential of destination zone too.

All working procedures were done on GIS software: ESRI© ArcGIS 10.1. We used a free tool for ArcGIS StreetDataProcessingTools to create our Network Dataset, and the Network Analyst's tools were used to create O/D cost matrix for each region and starting travel time interval. We used the travel time as impedance. Each cost route was calculated by taking into account the one-way edge and restricted turn, and by using hierarchal analysis (ESRI® 2013), because it largely improves computing performance and its results are generally quite similar to typical real shortest path. The result raster maps were done by IDW technique (specifications: power 2 distance decay function, with 12 points).

4.2. Results

On this subsection, we present primarily results of our research. In particular, we focused this paper on studying how congestion affects on origins accessibility according to equation 2. These have to be interpreted by their multiple behaviors, spatial and temporal, and particular and global.

4.2.1. Global impact of congestion

Using equation 3, we obtained the global impact of congestion weighted by population in both LUZs. A first interesting value, the referential one, is the maximum average accessibility value; it is 1,870,816 equivalent reachable population within 90 min travel time for Madrid and 1,443,195 for Barcelona. These values are strongly influenced by most populated areas accessibility performances.

As shown on figure 2, both study areas show similar pattern: the main accessibility reduction in morning peak and a secondary in afternoons. Between peaks, both have a stable accessibility value higher to 90% of free flow accessibility. In general, Madrid is more resilient than Barcelona, since the former worst global accessibility value worsen 13.41% respect the maximum and the latter is 15.58%. The difference between Madrid and Barcelona congestion impact generally remains constant during whole non-maximum accessibility value period.

4.2.2. Spatial and temporal impact of congestion

Global impact considers all LUZ as a whole, and it may fall people in wrong conclusions due to ecological fallacy. Moreover, global impact is a consequence of every part of the region and their interrelationships. Spatial and temporal impact explains where congestion affects and its magnitude.

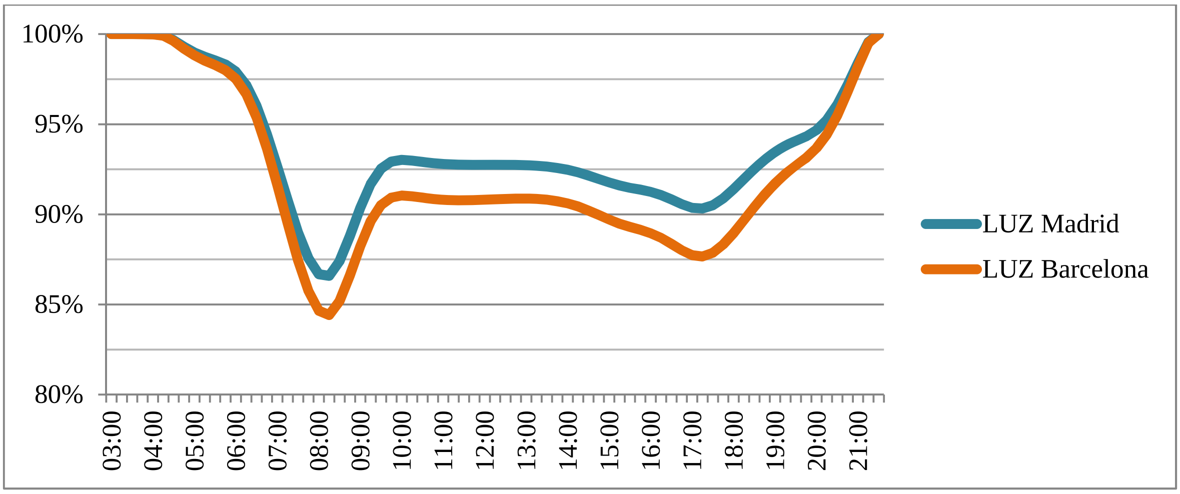


Figure 2: Relative Accessibility Weighted by Population for Madrid and Barcelona

On the one hand, using charts as shown in figure 2 but per each zone allow us to know when each zone is most affected by congestion. In both cases, whole LUZ's zones are hard affected in morning except downtowns (probably defining true main LUZ cores), which are in afternoons. Main airports are included in LUZ cores. Rest of zones has their morning worst accessibility value depending on network distance, as shown in figure 3.

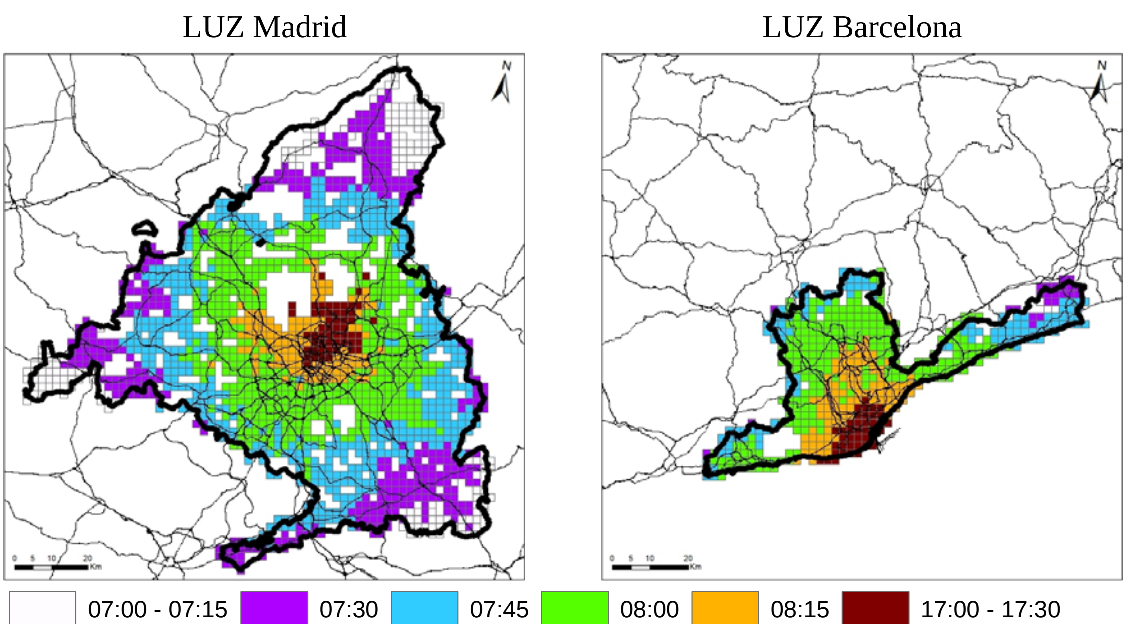
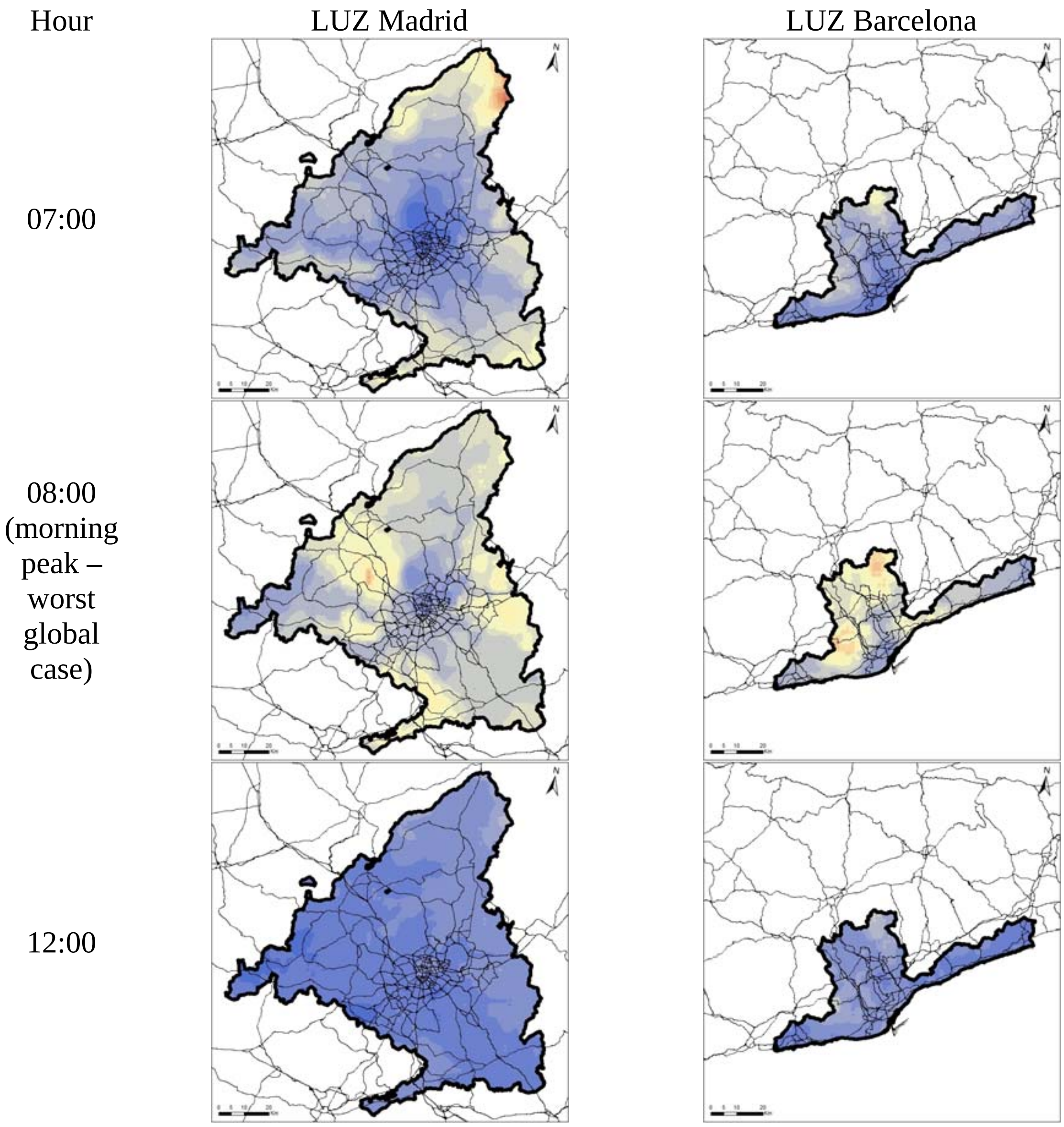


Figure 3: Hour of minimum accessibility per zone

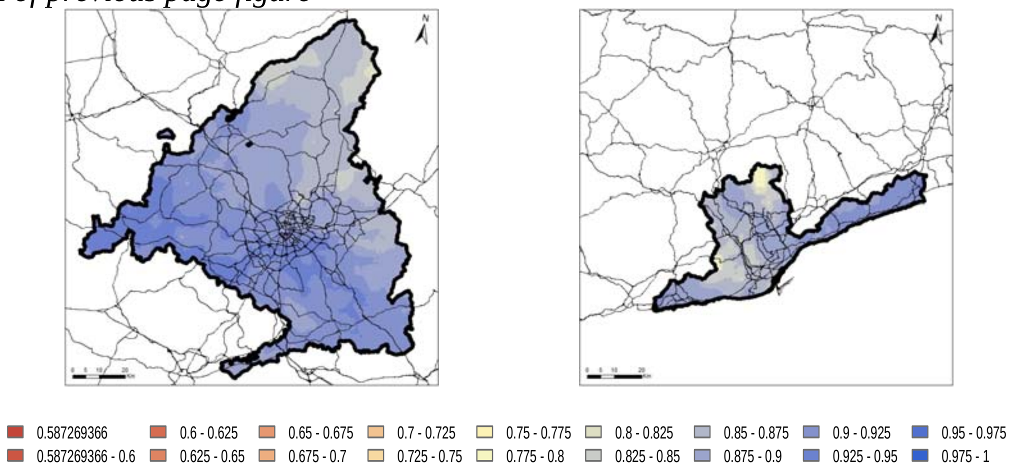
For instance, the north of Madrid (less populated zones), which is the most congestion harmed area, has its worst hour at 07:00, whilst the closest zones of LUZ cores has the worst hour at same time than global, at 08:00. As a consequence of this behavior, as shown in raster maps of congestion impact in figure 4, the worst accessibility time is at 8:00. At this time, both LUZs have high values of congestion impact on whole their areas, including on downtowns (the higher populated zones) as well.

On the other hand, peripheral zones showed different results, there may be zones can be located between two important zones as southwest region of Madrid and coastal limits of Barcelona. Their location can moderate the accessibility reductions since they can suffer geographically opposite important urban area congestion time at different times. It is also worth to mentioning that most populated zones have generally less congestion impact, because they not only have really high self-potential values but also they are generally surrounded by other high populated zones.



Continuation of previous page figure

17:00
(afternoon
peak)



Legend
(Rel.Acc)
1 = max. acc.

Figure 4: Comparing spatial distribution of congestion effects on both study LUZs

4.2.3. Impact of congestion on population

Population weights global impact, i.e. if there is any high-populated zone harmed by congestion, it tends to affect global. Figure 5 can explain why Barcelona shows worse congestion impact than Madrid, since it shows how is the population distributed by congested impact in both areas, and the variation of this impact.

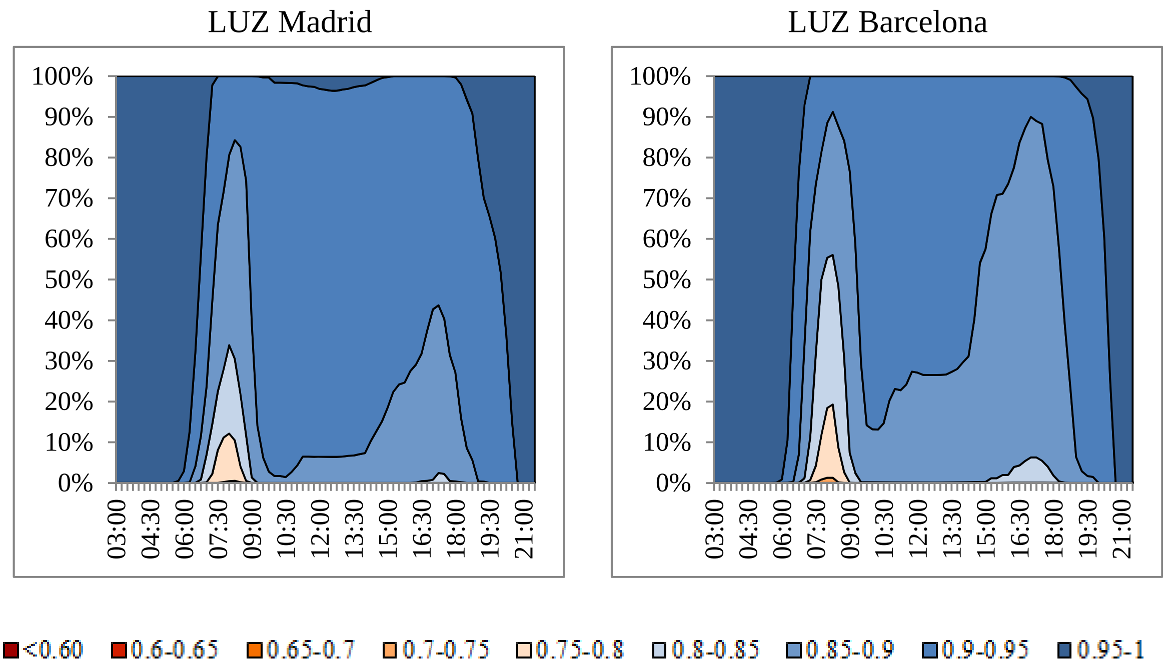


Figure 5: Relative population affected by congestion. Index based on Rel.Acc. per zone (where 1 is maximum accessibility)

Figure 5 confirms the differences between Madrid and Barcelona congestion impact in global either and local scope. Barcelona has not only more relative people hardly affected by congestion during both main peaks, but also it has not any population percentage with relative accessibility over 95% between peaks period. Besides, during non-maximum global accessibility period, Madrid can recover a higher accessibility value faster than Barcelona; any negative impacts are usually less steep for Madrid as well.

5. CONCLUSIONS AND FUTHER RESEARCH

Our investigation tries to enlarge the solution range of congestion problems into accessibility view. We are abandoning the traditional view of where congestion is happening (mobility concept) to who is affected, where they live, when they are affected and how much impact they suffer views. It conception is apparently more a consequence with sustainable mobility principles. Beside congestion may be good too, since it can favor more adequate policies and behaviors in each part and global of transport – land use – people system.

On this paper we measured the congestion impact for Madrid and Barcelona. The two cities show similar congestion impacts patterns, where a typical double peak impact: in mornings is the most important and a secondary congestion peak in evenings. However, Madrid is more resilient, in global values and temporal evolution of these impacts, than Barcelona. In any case, space-time distribution in both cities is similar and the airports are included on evening peak worse case zones. Besides, we can estimate a value of congestion between peaks, which can be more realistic than free flow value for measuring impacts and be more adequate policy indicators.

The chosen study areas might be controversial, since the chose area can bias the results. We are studying the congestion effects to other study areas delimitations and it shows same patterns and relative impacts than explained on this paper. The only exception is morning weak that it is less abrupt for smaller areas than global LUZ. Anyway, it seems that global relative accessibility value can fix some bias due to MAUP.

Despite our study is focus on origins, interesting view for any trip generator location policy as new residential, densification action or urban goods warehouses; we can use same procedure to destinations. Those new studies can be really useful for other location decisions, for instance in medical care centers, especially interesting in countries where emergencies are mainly managed by road transports.

Further than measuring congestion impact, the next steps for future research are to understand why those impacts occurs, in global accessibility view, and try to determinate what actions can be more interesting for general interests.

6. ACKNOWKEDGEMENTS

We are grateful to participants of NECTAR Cluster 6 on Accessibility and Policy Making on February 6 and 7, 2014 in Seville (Spain), for their comments, advices and their guidance. The authors also gratefully acknowledge Ministerio de Economía y Competitividad (Economy and Competitiveness Ministry) of Spanish Government for funding this research (Project SPILLTRANS, TRA2011-27095).

7. REFERENCES

BATTY, M. (2008). The Size, Scale, and Shape of Cities. *Science 319.* Pp. 769-771

BERTOLINI, L., LE CLERCQ, F. and 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. *Transport Policy 12,* pp. 207-220

CASAS, I (2003). Evaluating the importance of accessibility to congestion response using a GIS-based travel simulator. *Journal of Geographical Systems 5,* pp. 109-127

CHRISTIDIS, P. and IBÁNEZ RIVAS, J.N. (2012). *Measuring road congestion*. JRC Technical Notes. European Commission – Joint Research Centre – Institute for Prospective Technological Studies. Luxembourg (Luxembourg)

DAGANZO, C.F. (1999). Remarks on Traffic Flow Modeling and Its Applications. In: BRILON, W., HUBER, F., SCHRECKENBERG, M. WALLENTOWITZ, H. (Eds.) *Traffic and Mobility*. Springer-Verlag Berlin Heidelberg, Berlin (Germany)

DIJKSTRA, E.W. (1959). A note on two problems in connexion with graphs. *Numerische mathematic 1(1),* pp. 269-271

EEA (2009). *EEA reference grid.* Version uploaded on November 19, 2007.
[Permalink: 9B755D9F-8B6B-4CE0-9270-0963E10B2FC8. Last accessed on January 14, 2014]

EEA (2010). *Urban Atlas 2007 – 2010*. Version uploaded on May 28, 2010.
[Permalink: 9df69b925454fd267512ea65898dbbdc. Last accessed on January 14, 2014]

ESRI® (2013). About network analysis with hierarchy. *ArcGIS Help 10.1*. [http://resources.arcgis.com/en/help/main/10.1/index.html#//004700000057000000. Last accessed on January 21, 2014]

EUROSTAT (2009). *European Population Grid.* Downloaded on July 20, 2013. [Link: http://epp.eurostat.ec.europa.eu/portal/page/portal/gisco_Geographical_information_maps/popups/references/population_distribution_demography, Last accessed on January 20, 2014]

FROST, M.E. and SPENCE, N.A. (1995). The rediscovery of accessibility and economic potential: the critical issue of self-potential. *Environment and Planning A 27(11)*, pp. 1833-1848

GEURS, K.T. and RITSEMA VAN ECK, J.R. (2001). *Accessibility measures: review and applications. Evaluation of accessibility impacts of land-use transport scenarios, and related social and economic impacts. RIVM report 408505 006*. Rijksintituut voor volksgezondheid en milieu (RIVM), Bithoven (The Netherlands)

GOSPODINI, A. (2002). European Cities in Competition and the New “Uses” of Urban Design. *Journal of Urban Design 7(1)*, pp. 59-73

GUTIÉRREZ, J. (2001). Location, economic potential and daily accessibility: an analysis of the accessibility impact of the high-speed line Madrid-Barcelona-French border. *Journal of Transport Geography 9*, pp. 229-242.

HANSEN, W.G. (1959). How accessibility shape land use. *Journal of American Institute of Planners 25(1)*, pp. 73-76

INE (2004). Estudio de Movilidad Obligada (Commuting Study). *Censo de Población y Viviendas 2001. (Census of Population and Houses 2001)*

LEI, T.L. and CHURCH, R.L. (2010). Mapping transit-based access: integrating GIS, routes and schedules. *International Journal of Geographical Information Science 24 (2)*, pp. 283-304

LENNTORP, B. (1976). Paths in Space-Time Environments: A Time-Geographic Study of the Movement Possibilities of Individuals. *Lund Studies in Geography, Part B (44).*

LITMAN, T. (2013). *Smart Congestion Relief. Comprehensive Analysis Of Traffic Congestion Costs and Congestion Reduction Benefits.* Victoria Transport Policy Institute

MARTENS, M.J. and GRIETHUYSEN, S. V. (2000). *The ABC location policy in the Netherlands*. TNO Inro, Delft (The Netherlands).

MILLER, H.J. (1991). Modelling accessibility using space-time prism concepts within geographical information systems, *International Journal of Geographical Information System 5(3)*, pp. 287-301

MØLLER-JENSEN, L., KOFIE, R.Y. and ALLOTEY, A.N.M. (2012). Measuring accessibility and congestion in Accra, *Norsk Geografisk Tidsskrift – Norwegian Journal of Geography 66*, pp. 52-60

NEUTENS, T., SCHWANEN, T. and WITLOX, F. (2011). The Prism of Everyday Life: Towards a New Research Agenda for Time Geography. *Transport Reviews 31(1),* pp. 25-47

ORTÚZAR, J.D. and WILLUMSEN, L.D. (2001). *Modelling transport.* John Wiley and Sons, New York (United States of America)

QUIROGA, C.A. (2000). Performance measure and data requirements for congestion management systems. *Transportation Research Part C*, pp. 287-308

SCHALLABÖCK, K.O. and PETERSEN, R. (1998). Germany. In: ECONOMIC RESEARCH CENTRE – ECMT. *Traffic congestion in Europe. Report of the Hundred and tenth round table of transport economics, held in Paris on March 12-13, 1998.* OECD, Paris (France)

SCHRANK, D., EISELE, B and, LOMAX, T. (2012). *TTI's 2012 Urban Mobility Report.* Texas A&M Transport Institute – The Texas A&M University System

SIA, J.J., CHING, P.C. and RANJITKAR, P. (2009). Travel time study of Auckland arterial road network using GPS data. *Australasian Transport Research Forum (ATRF), 32nd, September 29 – October 1, Auckland (New Zealand).*

TOMTOM® (2013). *TomTom European Traffic Index*. TomTom International BV [http://www.tomtom.com/lib/doc/trafficindex/2013-1101%20TomTomTrafficIndex2013Q2EUR-km.pdf, January 13, 2014]

TUROK, I. and MYKHNENKO, V. (2007). The trajectories of European cities, 1960-2005. *Cities 24(3),* pp. 165-182

VANDENBULCKE, G., STEENBERGHEN, T. and THOMAS, I. (2009). Mapping accessibility in Belgium: a tool for land-use and transport planning? *Journal of Transport Geography 17,* pp. 39-53.

WEBER, J. and KWAN, M.P. (2002). Bringing Time Back In: A Study on the Influences of Travel Time Variations and Facility Opening Hours on Individual Accessibility. *The Professional Geographer 54(2),* pp. 226-240

WU, Y.-H., MILLER, H. J. and HUNG. M.-C. (2001). A GIS-based decision support system for analysis of route choice in congested urban road networks. *Journal of Geographical Systems 3*, pp. 3-24