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Measuring congestion in European cities

*A focus on Brussels, Seville
and Krakow*

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Abstract

Congestion is a major issue for cities and often a determining factor of connectivity within urban areas and intra-city interactions. It is a repercussion of the massive adoption of cars as the main transport mode and an externality related to the nature of cities as it represents the negative aspect of agglomeration, the major driving force of growth in cities.

We analyse the causes and impacts of congestion in order to be able to identify viable solutions against it. For this purpose, traffic needs to be studied at fine spatial and temporal resolution levels. We measure congestion at the level of Functional Urban Area considering the full transport network in order to estimate travel times between a large set of origins-destinations as determined by a high resolution population grid (size: 500mx500m). The impact of congestion is measured with the help of the relevant TomTom indicators that provide very detailed information on the variation of speed during the day at road link level.

Road traffic also affects accessibility. We measure accessibility using different operationalisations, with and without congestion, for all the populated grid cells in the functional urban areas of Brussels, Seville and Krakow. By analysing urban areas at such a fine spatial level we manage to capture the impacts of congestion in detail. This study is the first step towards the assessment and comparison of traffic in all European cities.

1 Introduction

Congestion is a major issue for cities and often a determining factor of connectivity within urban areas and for intra-city interactions. It is an externality directly related to the nature of cities as it represents the negative aspect of agglomeration, a major driving force of cities growth. Congestion is a consequence of the massive adoption of cars as the main transport mode, while the vast majority of measures against it aim to discourage the use of private vehicles within cities.

In order to better understand the causes and impacts of congestion, and be able to identify viable solutions against it, traffic needs to be studied at a fine level of spatial and temporal detail because it mainly affects specific network links at specific times of the day. In this study, we develop a framework of analysis of the impacts of congestion on accessibility and test it on three cities: Brussels, Seville and Krakow. The three cities have been selected for this pilot phase as they vary significantly in terms of geographic position, size, status of infrastructure, levels of congestion etc. The selection for this pilot was based on empirical considerations: Brussels is a capital city affected by high congestion, Seville is a medium-sized city with good road infrastructure and low levels of congestion and Krakow is a medium-sized city with less efficient infrastructure.

To represent congestion at its full spatial extent, the analysis is conducted at the level of Functional Urban Areas (FUAs) that include both the centre and commuting zone of cities (OECD, 2012). Furthermore, to capture the spatial detail of congestion the analysis is conducted at grid level (500mx500m). This level of spatial detail also allows the minimization of the impact of the internal distances in the calculation of accessibility indicators (Condeço Melhorado et al, 2016)

The direct impact of road congestion is the increase of travel times along congested network links. Detailed driving speed variation over the course of the day is available from Multinet (TomTom, 2015). These allow the estimation of congestion levels by comparing the speed on a specific link during a specific period to that that the link allows at free-flow conditions (Christidis & Ibañez, 2012).

The calculation of travel times between origin and destination zones is the most computationally intensive part of the process. The efficiency of the routing process during which travel times are calculated determines to a large extent the potentials of the analysis. It is important to be able to repeat travel time calculations for different hours and days in order to better represent the variation of congestion during the day.

As congestion varies throughout a city and during the course of the day, using data with high spatial and temporal resolution increases significantly the reliability of the estimation of impacts. At the same time, travel time calculations become more complicated because road network directions and restrictions become relevant. This happens because traffic information is link specific and as a result it is important to ensure that the path selection will be as realistic as possible.

Accessibility is measured using these travel times, applying different accessibility indicators. The characteristics of the case study and most importantly the research question determine the required elements of the indicator to be used. In this study, we are interested in measuring congestion with a methodology that can be applied in any European city using data that allow us to conduct the analysis at very fine resolution level.

A measure of the number opportunities accessible within a certain travel time is easy to interpret as it associates the impact of congestion with the loss of accessible opportunities. Such an indicator is useful for assessing the attractiveness of a location but not necessarily informative when comparing the transport systems of different cities because larger cities with a large concentration of opportunities or potential destinations will score higher in comparison to less densely populated cities. In order to control for the density of opportunities we calculate a relative measure of accessibility, namely transport performance, which practically weighs the number of opportunities reachable within a certain travel/driving time by the number of opportunities available within a certain distance. The transport performance indicator was developed jointly by the European Commission and International Transport Forum (ITF, 2019).

Furthermore, we calculate two accessibility indicators that allow to consider all the opportunities in the case study area: potential accessibility, a gravity-based measure (population over travel time) and location indicator which represent travel time weighted by the size of opportunities, i.e. population in the specific case.

The rest of the paper is structured as follows. The next section includes a review of studies regarding congestion and accessibility estimation framing our decisions in terms of methodology or data and

highlighting key points of this study. Then, the methodology description covers the travel time calculation and the accessibility indicators used. In the following section the population and road network data are described. Then, key results are presented both aggregated (at FUA or city level) and at grid level. Finally, the main conclusions are presented.

2 Congestion and accessibility

Congestion is one of the major transport issues cities are faced with. It is a negative outcome of agglomeration, the otherwise driving force of development in cities. Congestion affects primarily private transport but secondarily it has also an impact on public transport either because the two may share the same roads (Vandenbulcke et al, 2009; Rodrigue et al., 2014) or as a result of modal shift. Congestion is one of the main externalities of transport as it affects the travel time of all road users and has a direct impact on accessibility of destinations within a certain travel time. Accessibility indicators can properly assess the impacts of congestion because they capture the disruptions caused while they are easy to interpret (Vandenbulcke et al, 2009; Moya-Gómez and García-Palomares, 2015; Moya-Gómez and García-Palomares, 2017).

There are many definitions and indicators of accessibility addressing different aspects of the topic and covering specific assessment needs. Geurs and van Wee (2004) and Geurs and Ritsema van Eck (2004) provide a thorough review of accessibility indicators based on multiple criteria and taking into account different perspectives. They classify indicators in four main categories: infrastructure-based, location-based, person-based and utility-based indicators. The different categories aim to cover distinct areas of planning or assessment and use information at different levels of detail. The choice of the most suitable indicator depends on a combination of factors including data availability and type of analysis required. Selecting a more informative and detailed indicator is not necessarily the best choice because it might be difficult to obtain the required data. Lopez et al (2008) use four different accessibility indicators to measure how cohesion has changed over the years in Spain. Each indicator corresponds to different approaches, focusing on either the location or the infrastructure in combination with different measurement formulations. In particular, the population potential indicator or the daily accessibility indicator measure reachable population or activities, while the location indicator or network efficiency indicator use the population of destinations as weighting of travel cost measures.

Accessibility indicators considering the potential of locations to access opportunities are commonly used in transport and land-use planning and assessments (van Wee et al., 2001). They are quite informative incorporating both impedance and number of opportunities, flexible as they can be expressed in different functional forms and may include a decay function, while they are intuitive and straightforward in terms of interpretation.

Opportunities represent the attractiveness of a location as a destination: for commuting trips they can be referring to employment, while for shopping trips they may include shops, malls etc. Population is used as proxy for location attractiveness since population data are widely available and often, as in the specific study, at fine resolution level. The latter is particularly important to assess congestion in cities. As the analysis is taking place at 500mx500m grid level, the impact of intra-zonal accessibility – or 'autopotential' as defined by Geertman and Ritsema van Eck (1995) – is significantly reduced in comparison to performing the analysis at administrative level, because the representation of space approximates a continuous one as the size of the spatial unit of analysis (i.e. the grid cell) becomes smaller. Furthermore, the smaller the spatial unit the smaller the impact of the cut-off point determining accessible population within a certain time or radius.

However, Järv et al (2018) demonstrated that the conventional static location-based accessibility models tend to overestimate the access of people to potential opportunities. Adding the temporal dimension to accessibility indicators allows time-dependent factors to be taken into account. This is especially the case for analysing the impact of congestion, which can drastically affect access times to opportunities. Traffic in this study is represented with high temporal detail and the impacts of congestion are estimated at different times during a day capturing the variation of traffic over the course of the day.

3 Data

3.1 Origin-destination zones

The impacts of congestion are represented by the changes observed in accessibility. Population is aggregated in zones and accessibility is estimated for these zones. The smaller the zones are, the more precise the representation of the network becomes and it allows to better exploit link-level traffic information.

The FUA population is distributed to 500mx500m grid cells. The data are based on the 1km² population grid for year 2011 provided by EUROSTAT.

Destinations of trips vary over the course of the day. In a weekday morning, people will commonly commute to work, school or university, while in the evening they will return back home. Of course there are many other purposes for trips during the day. However, detailed travel demand information is not available.

Trip destinations are set to be the same as the origin zones, therefore accessibility refers, in this case, to the size of population within reach.

3.2 Road network

The complete road network is represented by Multinet data (TomTom, 2015) which allows for precise routing taking into account directions, access restrictions, road categories etc. This is particularly important at city level, because congestion appears on specific road segments and routing has to be as realistic as possible.

Multinet data provide a very detailed representation of the road infrastructure including variables relevant to the following:

- Identification of the road (e.g. name or code);
- Classification of the road (e.g. according to importance - highway, major road etc.) - or according to type of road - e.g. normal road, assistance lane, parking ramp etc.
- State of the road (e.g. construction status);
- Geo-locational characteristics;
- Direction of the road link;
- Length of the road link;
- Speed based on classification and type of the road;
- Time to traverse the link with this speed.

Furthermore, TomTom provides information on the variation of speed during the day due to changing traffic conditions. This is provided for the road segments where there is a sufficient number of GPS measurements by vehicles (probes) to estimate daily speed variations and it is used to associate these links with one of 293 available speed profiles. The speed profiles correspond to different patterns of variation of relative speed during a day and they include 288 values of relative speed for one day, i.e. one value for every five minutes. Speed profiles are provided for a typical week, i.e. one link might have different speed profiles in different days.

Speed profiles are available for almost all highways and major roads in European cities (Annex 1) while the coverage of the rest of the road classes varies from city to city.

Relative speed corresponds to the percentage reduction of free flow speed due to traffic, while free flow speed is measured in no-traffic conditions. Hence, free flow speed is not the same as the speed based on the classification and type of road. The average difference of the two speeds for each speed category as determined according to the classification and type of road is presented in Table 1 together with the corresponding standard deviation and distribution of the total road network to speed categories. As can be seen, free flow speed based on measurements is in general lower than network speed determined based on class and type of road.

Table 1: Difference between free flow speed and speed determined based on class and type of road. The last column for each city shows the breakdown of the network to different speed categories.

| Speed | Difference between free flow speed and network speed | | | | | | | | |
|------------|--|-------|----------------------|--------|-------|----------------------|---------|-------|----------------------|
| | Brussels | | | Krakow | | | Seville | | |
| | Mean | StDev | % of roads in FUA | Mean | StDev | % of roads in FUA | Mean | StDev | % of roads in FUA |
| 20 | 6 | 8 | 3.3 | 8 | 9 | 12.5 | 2 | 7 | 10.6 |
| 35 | -5 | 8 | 24 | 4 | 11 | 7.8 | -7 | 8 | 21.3 |
| 45 | -7 | 11 | 22.1 | 4 | 12 | 24.8 | -9 | 12 | 17.8 |
| 50 | -8 | 14 | 9 | 2 | 14 | 1.7 | -1 | 18 | 4.5 |
| 60 | -13 | 14 | 10.1 | -1 | 13 | 13.6 | -16 | 17 | 2.4 |
| 65 | -16 | 13 | 16.5 | -8 | 11 | 20.2 | -2 | 18 | 22.6 |
| 70 | 10 | 14 | 0.5 | -5 | 14 | 1.6 | 4 | 15 | 0.8 |
| 75 | -15 | 17 | 9.6 | -9 | 13 | 11.8 | 1 | 19 | 12 |
| 85 | -40 | 19 | 0.1 | -5 | 7 | 1.7 | | | |
| 100 | -17 | 20 | 1.1 | -18 | 13 | 0.9 | -18 | 9 | 0.7 |
| 120 | -12 | 10 | 3.8 | -5 | 12 | 3.4 | -14 | 13 | 7.3 |

4 Methodology

The analysis is carried out at grid level (500mx500m grids) using the complete road network. The impacts of congestion are represented by the differences of accessibility between traffic and no-traffic conditions. Accessibility is estimated for each populated grid cell in the FUA by considering driving time to all potential destinations. Destinations are considered to be all populated grid cells.

A FUA consist of the city and its commuting zone which may include suburbs and surrounding towns or villages. The total population of the FUA of Seville is more than 1.5 million inhabitants distributed to almost two thousand grid cells (500mx500m), for Brussels it is more than 2.5 million people distributed to almost eleven thousand grid cells, while for of Krakow it is less than 1.4 million people distributed to almost twelve thousand grid cells. Hence travel times for Seville are calculated for almost 3.5 million shortest paths connecting all the population grid cells, while travel times for Brussels and Krakow are calculated for more than 100 million shortest paths. These calculations are repeated as many times as the number of different traffic conditions considered, more specifically, one time without congestion and then over the course of the day to consider congestion.

For the no-traffic scenario, travel times are estimated using the free flow speed provided by the Multinet data. More information can be found in the data section. For the traffic scenarios, travel times are calculated hourly during a weekday (Tuesday) using driving speeds corresponding to different congestion levels. The morning peak generally occurs between 8:00 am and 9:00 am.

By averaging speed over a time period (e.g. the morning or evening peak) the impacts of congestion become smoother. However, if the period is carefully selected then the measure can well represent congestion during peak time.

4.1 Travel time calculation

The calculation of driving time is fundamental for this analysis. At first, to represent congestion in cities and take full benefit of link level information on congestion it is necessary to analyse cities in as many zones (smaller areas or grids) as possible and use a precise representation of the road network. As a result, network modelling becomes complex and demanding in terms of computational resources.

The network analysis algorithms and processes have been developed using the programming language Python. The road network is represented as a directed multigraph and every edge contains driving time information under different traffic conditions which is used to calculate the shortest paths between origins and destinations.

The major steps for the estimation of shortest paths are the following:

1. The speed in traffic conditions is calculated by averaging relative speed over the selected time period (e.g. hourly). When data on speed profiles and free flow speed are not available, speed is set to be equal either to the average speed for the specific functional road class in the area or to the speed limit of the specific road link, whichever is lower. Then, for each road link, driving times in free-flow and congestion conditions are estimated.
2. The road network is loaded as a directed multigraph and the driving times calculated in the previous step are included as attributes of the edges. They will be the weights on which the shortest path estimation will be based. Directions are carefully respected to ensure that traffic flows are correctly allocated.
3. Finally, the shortest paths from all origins to all destinations are calculated using the Dijkstra algorithm (Dijkstra, 1959) for different traffic (or no-traffic) conditions. Origins and destinations are the centroids of the grid and the actual shortest path calculated is the one between the closest nodes of the road network to the origin and destination respectively. The final output table includes the following variables:
 - (a) Reference ID of the origin and destination grid cells;
 - (b) Straight line distance between the origin and destination grid cells;
 - (c) Travel/driving distance between the origin and destination grid cells;
 - (d) Travel/driving time between the origin and destination grid cells.

These variables are then used to aggregate the results and calculate accessibility indicators.

4.2 Accessibility indicators

Different formulations of accessibility indicators tend to address specific dimensions of the relationship of a point in space with its surroundings. For example, using the classification of Geurs & van Wee (2004) and Geurs & Ritsema van Eck (2004), infrastructure-based indicators consider the quality of service (travel time, congestion time etc.) but ignore issues related to activities in the destinations. On the other hand, location-based accessibility measures include both a measure of opportunities in the destination zone and a measure of distance or cost of travel between the origin and destination zones. Furthermore, potential accessibility indicators include a sensitivity parameter –e.g. a decay function – that aims to capture spatial travel behaviour. Location-based and potential accessibility indicators are the most relevant to the purposes of this study as they can analyse performance including a measure of importance of destinations.

For the specific question analysed here four types of operationalization of accessibility indicators are used that quantify four underlying aspects relevant to the spatial relationships within cities:

- Absolute accessibility as an absolute measure of opportunities reachable within a certain travel time
- Transport performance as a relative measure of opportunities controlling for the size of city
- Location indicator as a measure of a zone's connectivity
- Potential indicator as a measure of a zone's access to all opportunities

In general, the scale of application dictates the choice of indicators, variables and methods. The combination of population data at grid level and a very detailed road network makes this analysis unique. At the same time, processing data of such detail and size is quite challenging.

4.2.1 Absolute accessibility

Absolute accessibility belongs to the cumulative accessibility indicators and refers to opportunities reachable within a certain travel/driving time (Handy and Niemeier, 1997; Lopez et al 2009). The determination of travel time varies from case to case. In the specific one where we are interested in daily urban trips in a medium sized city, the limit has been set to half an hour which is slightly higher (less than 5 minutes) than the average travel time connecting all origins and destinations. Absolute accessibility is given by the following formula:

$$AA_{i\kappa} = \sum_{j=1}^n P_j \delta_{ij}$$

where:

P_j the population of destination zone j as in the specific case opportunities are represented by population;

δ_{ij} a binary variable equal to 1 when travel time from zone i to zone j is smaller than the determined travel time κ (30 minutes in our case) and 0 otherwise, and

n the number of destination zones to be taken into account in the calculation (all in the specific case).

The indicator measures accessible population and congestion will have a negative impact by increasing travel time i.e. reducing the number of destinations reachable in 30 minutes. The impact might appear to be disproportionate when driving time increase will bring densely populated zones out of the half hour limit. Being an absolute measure this indicator is affected by the size and density of the FUA; the impact of traffic will be captured by the relative variation of absolute accessibility with and without congestion.

4.2.2 Transport performance

As absolute accessibility grows together with the density of available opportunities within reach it is not appropriate to assess the efficiency of a city's transport network. In order to control for the density of opportunities we calculate a relative measure of accessibility which benchmarks the number of opportunities reachable within a certain travel/driving time by the number of opportunities available within a certain radius. This transport performance indicator is calculated by the following formula (ITF, 2019):

$$TP_{i\kappa\lambda} = \frac{\sum_{j=1}^n P_j \delta_{ij}}{\sum_{j=1}^n P_j \rho_{ij}}$$

where:

P_j the population of destination zone j as in the specific case opportunities are represented by population;
 δ_{ij} a binary variable equal to 1 when travel time from zone i to zone j is smaller than the determined travel time κ (30 minutes in our case) and 0 otherwise;

ρ_{ij} a binary variable equal to 1 when distance from zone i to zone j is smaller than the determined distance λ (10 kilometres radius) and 0 otherwise;

n the number of destination zones to be taken into account in the calculation (all in the specific case).

By increasing travel times, congestion will reduce the number of accessible destinations from each grid cell, returning lower transport performances compared to free-flow speeds.

4.2.3 Location Indicator

The location indicator measures the average travel time from a cell to all the surrounding destinations, weighted by the population of destinations. This indicator should be interpreted from a locational perspective as it represents the travel time between a location and a number of points of interest (Gutierrez, 2001). It is given by the following formula (Gutierrez et al, 1996):

$$LI_i = \frac{\sum_{j=1}^n t_{ij} P_j}{\sum_{j=1}^n P_j}$$

where:

t_{ij} the travel time from cell i to destination zone j ;

P_j the population of destination zone j ;

n the number of destination zones to be taken into account in the calculation (all in the specific case).

The indicator is expressed in time units, and its physical interpretation is how long on average it takes to drive from each zone to the activities. Travel times are calculated separately for each destination. The impacts of congestion will translate to higher average travel times and higher values for this indicator.

4.2.4 Potential Accessibility Indicator

The third indicator used is potential accessibility (Hansen, 1959), which is classified as a gravity-based indicator considering the way it incorporates travel time. Travel time is raised to the power of α in order to control the importance of the role of distance, or time, between origin and destination. Values larger than 1 (i.e. a higher decay function parameter) increase the importance of relations over short distances (Gutierrez, 2001).

$$PA_i = \sum_{j=1}^n \frac{P_j}{t_{ij}^\alpha}$$

where:

t_{ij} the travel time from cell i to destination zone j

P_j the population of destination zone j

n the number of destination zones to be taken into account in the calculation (all in the specific case)

α is a parameter to control the decay function

This indicator should be interpreted from an economic perspective as it measures the economic potential of each place considered and the changes to be caused by new infrastructure (Gutierrez, 2001). As in the case of the other indicators, population P is used as a proxy of the opportunities that can be accessible.

The simplest formulation uses parameter $\alpha = 1$, which corresponds to a linear decay function. The value of the resulting indicator for each cell is proportional to the sum of population accessible from the cell per unit of travel time. By increasing travel times, congestion will impact negatively the grid cells which become harder to access, hence returning lower values for this indicator.

4.2.5 Summary of accessibility indicators

The absolute accessibility indicator is sensitive to the exogenously defined travel time threshold. While this allows a direct physical interpretation (number of persons reached within a 30 min drive), the fixed radius used in the calculation may cause the indicator to depend excessively on the population density of the cells in the area covered. Transport performance controls for the density of opportunities by dividing the number of opportunities reachable within a certain driving time by the number of opportunities available within a certain distance. The potential accessibility indicator has a direct physical interpretation (average number of persons reached per unit of driving time across the whole FUA). It avoids the fixed radius limitation, but instead depends on the size, form and population distribution of the FUA. It nevertheless offers the advantage of allowing different decay functions (α parameter with values different than 1) that could be used to limit such distortions. The location indicator measures travel time and uses the weights of the destination cells population, in practice normalizing the results. The normalisation of the indicator offers the major advantage of allowing comparisons across different FUAs using the same easily interpretable indicator.

5 Results

The accessibility indicators have been estimated at grid level and then aggregated to estimate total accessibility for the FUA, city and commuting zone. The variation of total accessibility during the day can indicate peak and off-peak times of congestion and the analysis of the results at grid level the areas mostly affected by congestion.

5.1 Total accessibility

The indicator of total accessibility for the FUA, city or commuting zone is calculated as the population weighted average of grid level accessibility according to the following formula.

$$Acc_{Tot} = \frac{\sum_{i=1}^n Acc_i P_i}{\sum_{i=1}^n P_i}$$

where,

Acc_i is the value of an accessibility indicator for cell i and it can refer to any of the four indicators considered, i.e. absolute accessibility, transport performance, location indicator and potential indicator,

P_i is the population of cell i ,

n is the total number of populated grid cells in the FUA, city or commuting zone.

The aggregate results for hourly variation of absolute accessibility in Brussels, Krakow and Seville are illustrated in Figure 1 while in Figure 2 are presented the hourly variations of absolute accessibility and average speed for Seville.

The variation of total accessibility during the day closely follows that of average speed along the network. Average speed \bar{v} , an indicator of the road network's level of service, is calculated as:

$$\bar{v} = \frac{\sum_{i=1}^n \sum_{j=1}^n v_{ij} P_i P_j}{\sum_{i=1}^n P_i \sum_{j=1}^n P_j}$$

where,

v_{ij} is the average speed between each cell combination ij ;

P_i, P_j the respective populations of cells i and j .

The aggregate results clearly indicate the existence of a morning peak between 8:00 and 9:00 for the three cities but the afternoon peak appears to be smoother for Seville. The hourly variation in Seville appears to be smoother in Figure 1 than in Figure 2 as a result of the different scale of the y axis.

Figure 1: Hourly variation of absolute accessibility in Brussels Seville and Krakow

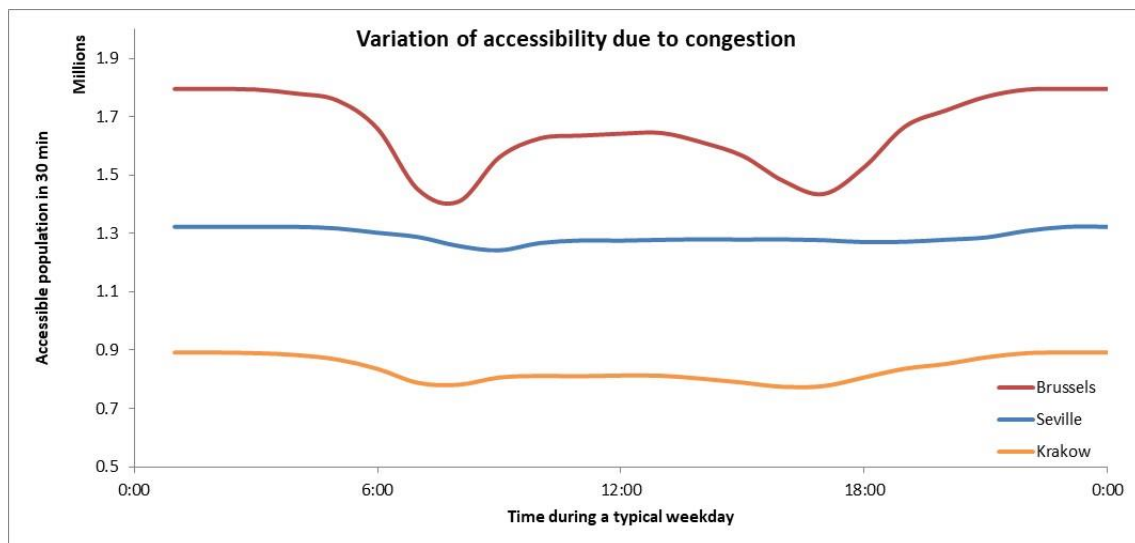
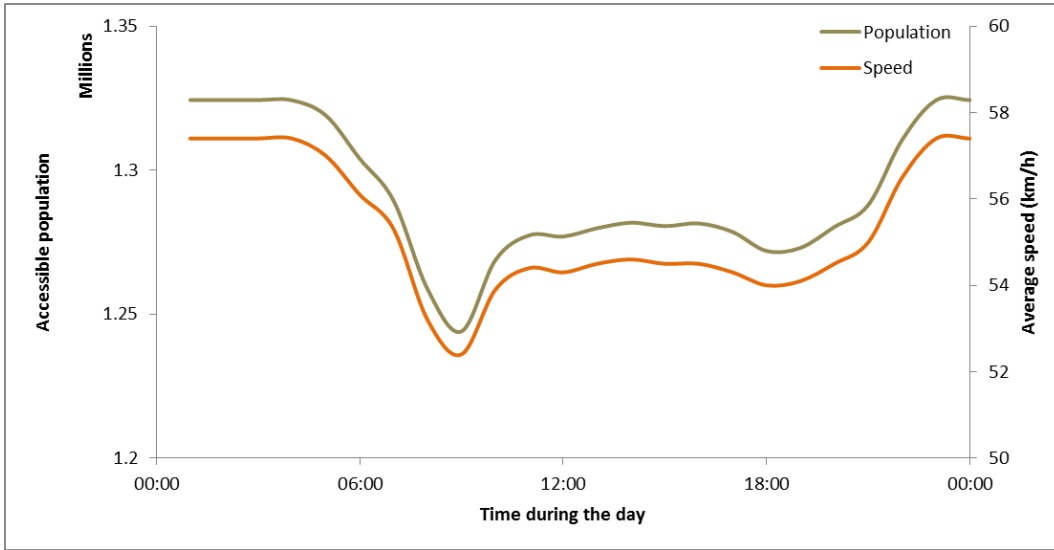


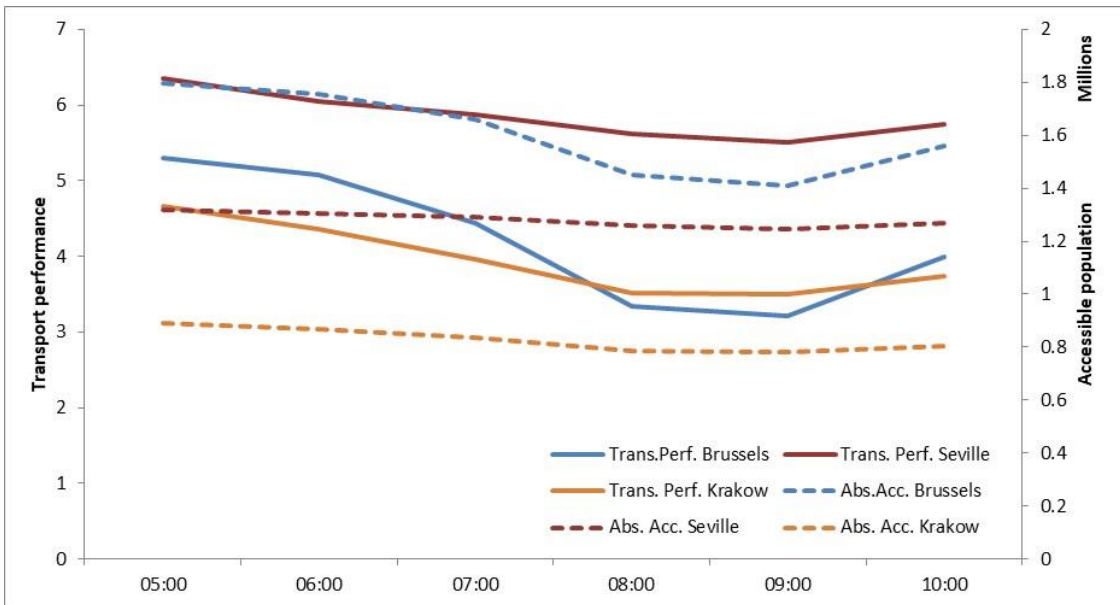
Figure 2: Hourly variation of absolute accessibility and speed during a day in Seville



The morning variation of transport performance and absolute accessibility for the three cities is displayed in Figure 3. The levels of absolute accessibility indicate that Brussels performs best among the three cities. This is because Brussels is a large and dense city offering good access to many opportunities. However, according to the results of transport performance Seville comes first, indicating that the road network of Seville performs best offering better access to nearby opportunities. Accessibility in Krakow is lower than in Brussels or Seville according to both transport performance and absolute accessibility which means that, comparatively, in Krakow there is lower access to fewer opportunities.

Particularly interesting appears to be the impact of congestion. Brussels is the city most affected by congestion as the drop of accessibility is sharper than in Seville or Krakow, while during the morning peak transport performance of Brussels falls below that of Krakow.

Figure 3: Morning variation of transport performance and absolute accessibility in Brussels, Seville and Krakow



Furthermore, we distinguish between the city and the commuting zone and the results are presented in Table 2. In general, absolute accessibility in cities is always higher than in the commuting zones because cities have higher population density. On the other hand, transport performance in commuting zones is higher than in cities because the speed limits are higher. As can be seen in Table 2, the impact of congestion on transport performance in commuting zones is higher than in the core of the cities.

Table 2: Percentage change of transport performance due to congestion (morning peak 08:00-09:00) in the city and commuting zone

| | Brussels | Seville | Krakow |
|----------------|----------|---------|--------|
| City | -9% | -4% | -8% |
| Commuting Zone | -44% | -17% | -29% |

5.2 Grid accessibility

The grid level results are presented in maps of accessibility in free flow and congested conditions at four different times of the day. The peak times of the day have been determined based on the absolute and local minima of the accessibility indicators. For all three cities they correspond to 8:00-9:00 (morning peak) and 17:00-18:00 (evening peak).

5.2.1 Comparison of accessibility at grid level in Brussels, Seville and Krakow

At first, the impacts of congestion in the three cities are compared. Figures 4 and 5 illustrate the impact of congestion (morning peak) at grid level on absolute accessibility and transport performance, respectively. Obviously, the impact is significantly lower in Seville than in the other two cities. At grid level it is possible to identify the areas worst affected and in the case of Seville it is the suburbs in the western part of the city. Both in absolute and proportional terms, Brussels is the city worse affected by congestion. This becomes clearer in Figure 5 where the percentage change of transport performance is presented.

Figure 4: Absolute changes of absolute accessibility (accessible population in 30 min.) due to congestion at the morning peak (starting from top left and moving clockwise: Brussels, Seville, Krakow)

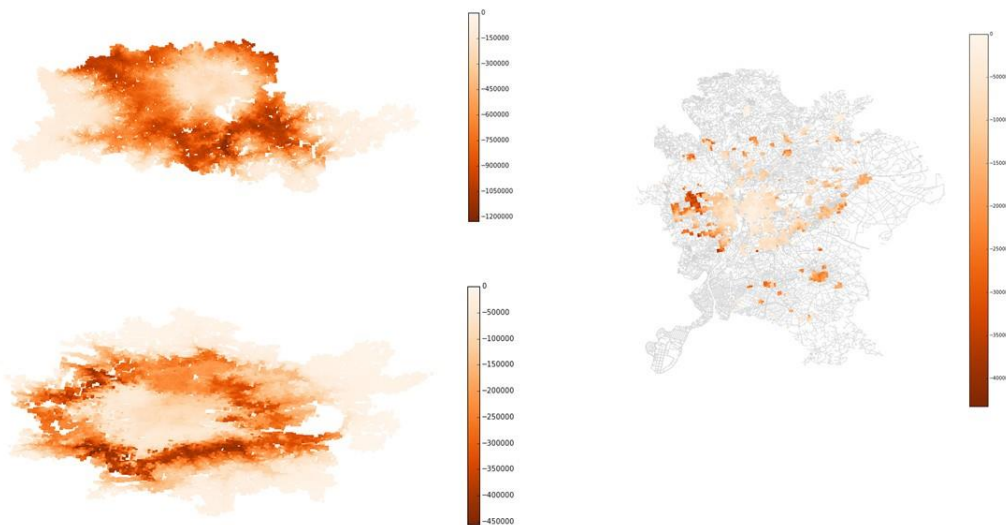
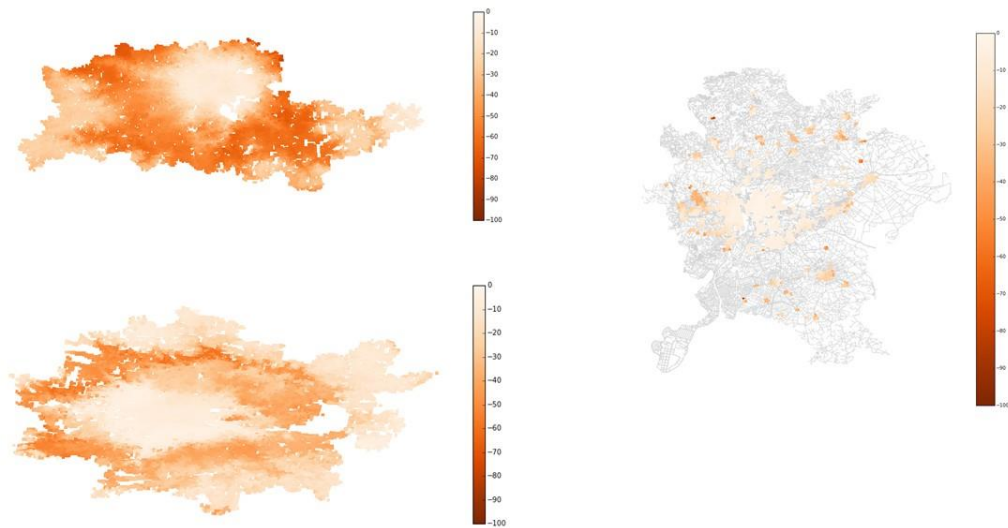


Figure 5: Percentage changes of transport performance (accessible population in 30 min./population within 10 kilometres) due to congestion at the morning peak (starting from top left and moving clockwise: Brussels, Seville, Krakow)



5.2.2 Accessibility at grid level in Seville

Figure 6 displays the absolute changes of absolute accessibility due to congestion and Figure 7 the percentage changes of transport performance at different times of the day including morning peak, mid-day, evening peak and night. The pattern of hourly variation of total absolute accessibility is also observed here with a clear impact of congestion during the morning peak and a milder one during the afternoon peak. The impacts are higher in the western part of Seville which is mainly a residential area where significant part of the population works in or around the centre of the city. In contrast, the impacts in the centre of Seville appear to be less important. The reason is that the centre is more densely populated. Hence, the increase of travel time due to congestion will affect more the population accessible in half hour from a grid cell in the suburbs that cannot anymore reach a densely populated grid cell in the centre of the FUA. On the other hand, the densely populated centre appears to be less affected by congestion because the population living there will still be able to access their neighbouring or close-by densely populated grid cells within half hour and will lose access to more sparsely populated ones.

Figure 6: Absolute changes of absolute accessibility (accessible population in 30 min.) due to congestion at different times of the day (starting from top left and moving clockwise: 08:00-09:00, 13:00-14:00, 17:00-18:00 and 22:00-23:00)

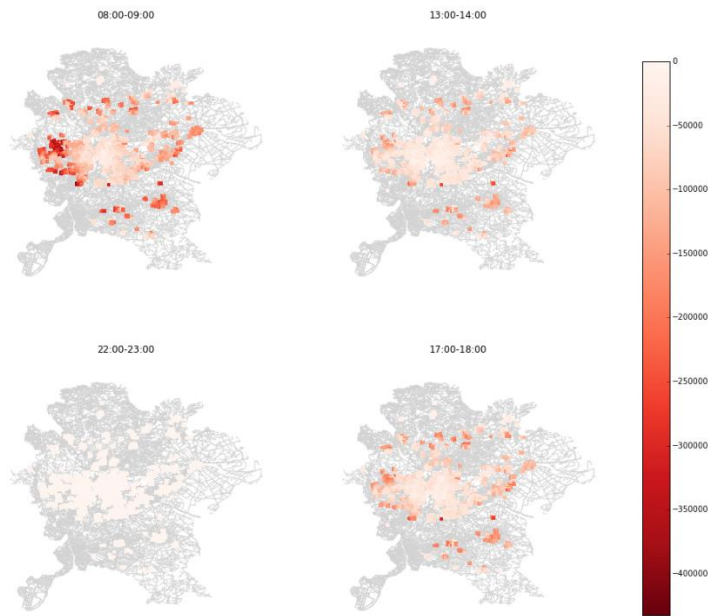


Figure 7: Percentage changes of transport performance due to congestion at different times of the day (starting from top left and moving clockwise: 08:00-09:00, 13:00-14:00, 17:00-18:00 and 22:00-23:00)



The spatial distribution of temporal absolute changes of the potential indicator shows a different picture in comparison to absolute accessibility. Figure 8 illustrates the absolute changes of the potential indicator due to congestion at different times of the day including morning peak, mid-day, evening peak, and night. As the potential indicator does not include a cut-off point it is not so sensitive to the distribution of opportunities (population). As a result of congestion in or around the densely populated centre, the centre of Seville is the area mostly affected in absolute terms from the perspective of the potential indicator. However, in relative terms (Figure 9) the western part of Seville remains the one mostly affected by congestion. During the morning peak, the impacts extend to the west of the centre. The potential indicator weighs opportunities by travel time representing the gravity modelling approach according to which accessibility is inversely proportional to time and proportional to the population of destination zones. This is also reflected in our results which show the impact of the increase of travel time to the densely populated zones in the city centre.

Finally, the location indicator that measures the impacts on travel time weighted by the amount of opportunities (i.e. population in this case) indicates the commuting zone to the west of Seville as the one mostly affected by congestion. In Figure 10 are illustrated the absolute changes of the location indicator due to congestion at different times of the day including morning peak, mid-day, evening peak, night. The location indicator appears to be more sensitive in comparison to absolute accessibility or transport performance as it manages to capture impacts for a larger number of grid cells. The reasons are that it does not have a cut-off point while the range of impacts goes up to five minutes which means that changes of less than one minute are also shown.

Figure 8: Absolute changes of the potential indicator (accessible population) due to congestion at different times of the day (starting from top left and moving clockwise: 08:00-09:00, 13:00-14:00, 17:00-18:00, 22:00-23:00)

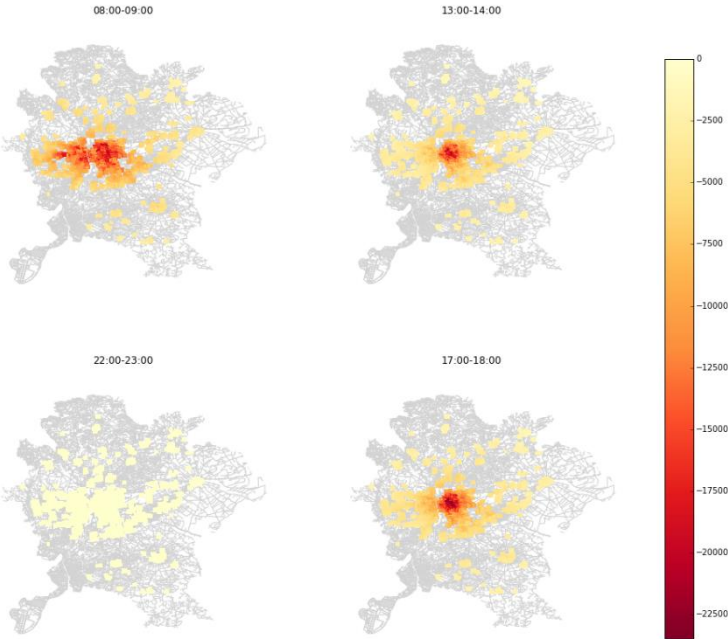


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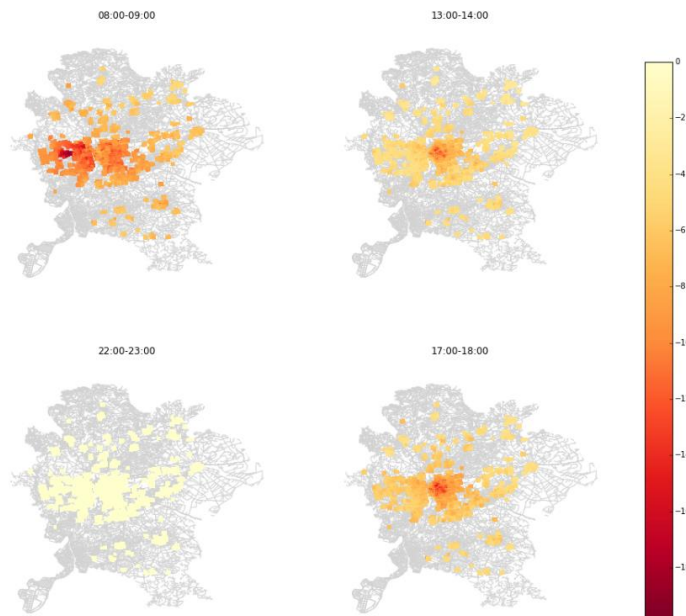
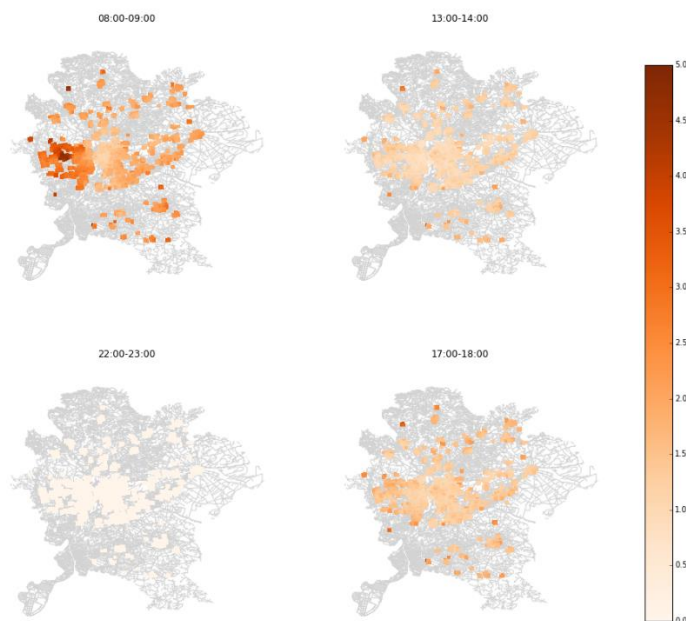


Figure 10: Absolute changes of the location indicator (travel time in minutes to opportunities) due to congestion at different times of the day (starting from top left and moving clockwise: 08:00-09:00, 13:00-14:00, 17:00-18:00, 22:00-23:00)



5.2.3 Accessibility at grid level in Brussels

Figure 11 displays the results of absolute accessibility at different times of the day including early morning, morning peak, mid-day, evening peak. For the same times of the day, Figure 12 displays the percentage changes of transport performance due to congestion, Figure 13 the absolute changes of the potential indicator which refer to accessible population and Figure 14 the absolute changes of the location indicator measured in minutes. In all figures is obvious the impact of congestion during the morning and evening peaks. The decrease of accessibility, transport performance and driving time (location indicator) due to congestion appears to be larger in the surrounding areas than in the centre indicating that the suburbs are those mainly affected by congestion as a result of the fact that congestion disrupts the access from the suburbs to the densely populated centre. Quite interesting is the difference of the impacts on potential accessibility between the morning and evening peaks as presented in Figure 13. The impact of congestion during the morning peak appears to be extended to a large part of the commuting zone, while during the evening peak the impacts are more concentrated in and around the core of the city.

Figure 11: Absolute accessibility (accessible population in 30 min.) at different times of the day (starting from top left and moving clockwise: 05:00-06:00, 08:00-09:00, 13:00-14:00, 17:00-18:00)

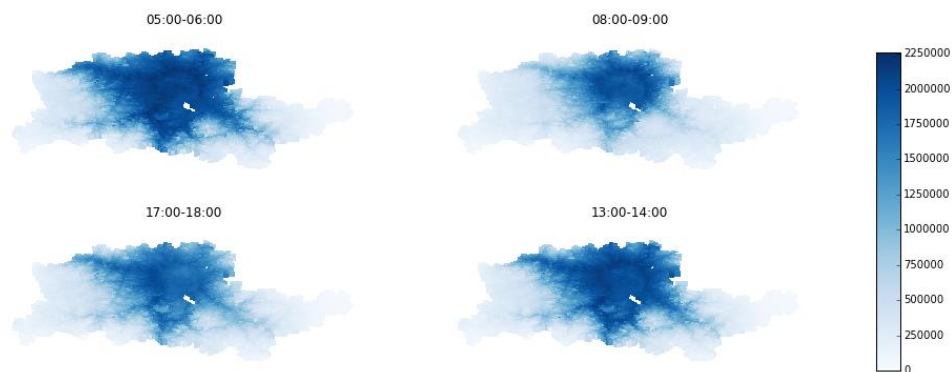


Figure 12: Percentage change of transport performance (population accessible within 30 min. over population within 10km) due to congestion at different times of the day (starting from top left and moving clockwise: 05:00-06:00, 08:00-09:00, 13:00-14:00, 17:00-18:00)

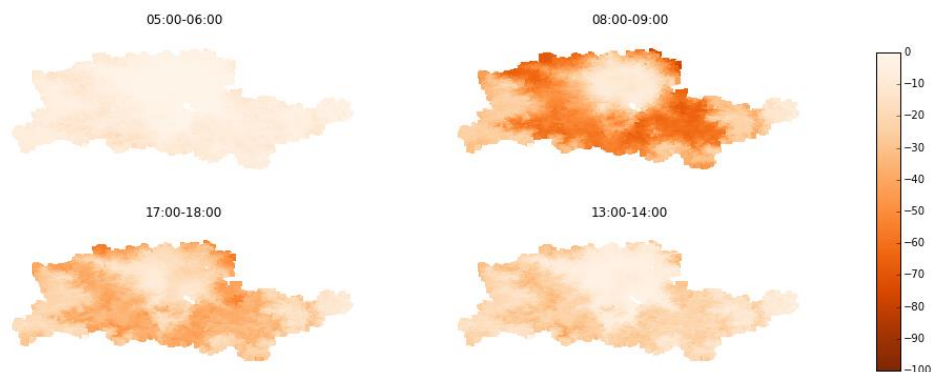


Figure 13: Absolute changes of the potential indicator (accessible population) due to congestion at different times of the day (starting from top left and moving clockwise: 05:00-06:00, 08:00-09:00, 13:00-14:00, 17:00-18:00)

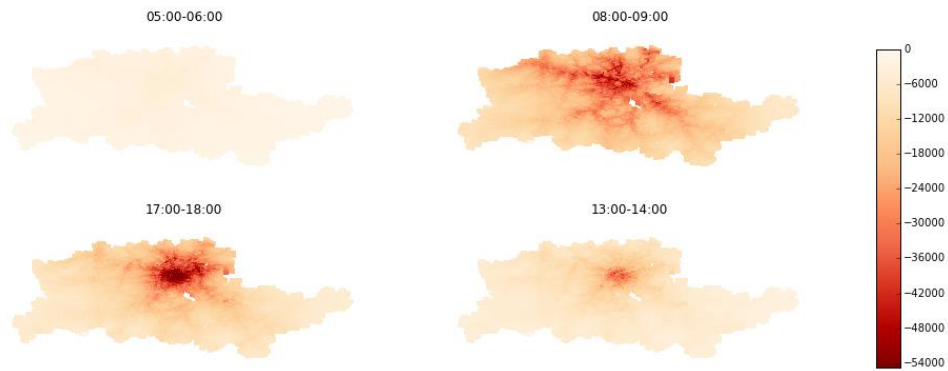
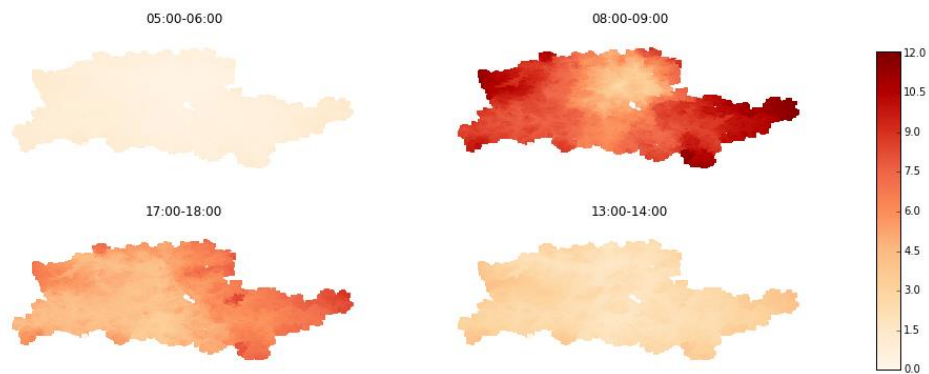


Figure 14: Absolute changes of the location indicator (travel time) due to congestion at different times of the day (starting from top left and moving clockwise: 05:00-06:00, 08:00-09:00, 13:00-14:00, 17:00-18:00)



6 Conclusions

We combined detailed speed measurements and accessibility indicators at very fine spatial resolution in order to explore the impact of congestion on accessibility within a city. Using Brussels, Seville and Krakow as case studies for our proposed methodology we can conclude that there is a direct link between congestion and decrease in accessibility, while accessibility indicators are suitable to capture the impacts of congestion. In particular for measuring the impacts on travel time, the location indicator provides a direct indication of the impact of congestion on driving time taking into account the distribution of all opportunities in the case study area.

Apart from the obvious relationship between travel times and accessibility, congestion also affects both the spatial and temporal patterns of accessibility. Given the fluctuations of travel demand and congestion depending on the day or time in combination with the trips' origin and destination, accessibility analysis at urban level should be extended to take those aspects into account.

From the three cities considered, Brussels is the city more affected by congestion as transport performance is almost halved during the morning peak. Krakow appears to be the city with the worst performing transport infrastructure (without congestion) and Seville has the lowest traffic. As a result of the structure of the FUA, the spatial distribution of loss in accessibility is not uniform. Perhaps surprisingly, Seville has only one clear peak period, during the morning hours. Working hours seem to play a role, most activities (distribution, work, school, shops) start between 6:00 am and 10:00 am, but return trips seem to cover a much wider period (from 2:00 pm to 11:00 pm).

The framework of analysis presented here is easily replicable in other cities. However, additional tests in different cities are necessary in order to test the robustness of the approach. The impact of FUA size, structure and mobility patterns do play a role in the measurement of accessibility and most probably also affect the measurement of the impact of congestion. The results of the test in three cities suggest that the approach is suitable for monitoring the spatial and temporal patterns of congestion-accessibility impacts for a specific city and for comparing different cities.

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Annexes

Annex 1. Road network and speed profiles

The classification of roads into Functional Road Classes (FRCs) is made by TomTom (2015). Classes 0, 1 and 2 refer to highways and major roads, classes 3, 4 and 5 to secondary roads and important local roads, and classes 6, 7, 8 to local or other roads of less importance. The total length of road networks within FUAs (FRC 0-7) in 29 countries (EU28 + CH + NO, without CY) is 3 million km.

Table A1: Length of network within FUAs by FRC group, 29 countries

| | Length | Share of total (%) |
|----------|--------------|--------------------|
| FRC 0 -2 | 230 191 km | 5 |
| FRC 3 -5 | 670 179 km | 21 |
| FRC 6 -7 | 2 180 453 km | 73 |

Table A.2: Length of network within FUAs by FRC group, country level

| | Total network length (km) | Share FRC 0-2 (%) | Share FRC 3-5 (%) | Share FRC 6-7 (%) |
|----|---------------------------|-------------------|-------------------|-------------------|
| AT | 50049 | 10 | 27 | 64 |
| BE | 46782 | 11 | 24 | 65 |
| BG | 25624 | 12 | 34 | 54 |
| CH | 23970 | 11 | 26 | 63 |
| CZ | 46873 | 9 | 29 | 61 |
| DE | 609895 | 10 | 22 | 68 |
| DK | 38408 | 5 | 16 | 79 |
| EE | 16390 | 4 | 18 | 78 |
| EL | 43518 | 5 | 25 | 71 |
| ES | 282625 | 6 | 18 | 77 |
| FI | 79937 | 4 | 18 | 78 |
| FR | 525896 | 8 | 23 | 69 |
| HR | 37251 | 6 | 18 | 76 |
| HU | 53668 | 7 | 21 | 72 |
| IE | 30867 | 7 | 19 | 74 |

| | | | | |
|----|--------|----|----|----|
| IT | 276315 | 6 | 20 | 75 |
| LT | 15678 | 5 | 21 | 74 |
| LU | 7900 | 10 | 35 | 55 |
| LV | 23710 | 4 | 19 | 77 |
| MT | 2708 | 3 | 16 | 81 |
| NL | 101998 | 8 | 22 | 70 |
| NO | 40425 | 6 | 19 | 76 |
| PL | 186616 | 6 | 24 | 70 |
| PT | 50138 | 6 | 23 | 71 |
| RO | 26985 | 11 | 14 | 75 |
| SE | 107385 | 5 | 14 | 81 |
| SI | 28353 | 4 | 13 | 83 |
| SK | 15753 | 9 | 20 | 71 |
| UK | 285109 | 8 | 27 | 66 |

Table A.3: Share of network with speed profile by FRC group

| Country | Share of FRC0-2 with speed profile (%) | Share of FRC3-5 with speed profile (%) | Share of FRC6-7 with speed profile (%) |
|---------|--|--|--|
| AT | 99.0 | 76.6 | 13.6 |
| BE | 99.7 | 91.4 | 22.2 |
| BG | 83.4 | 11.9 | 0.6 |
| CH | 99.8 | 95.0 | 26.9 |
| CZ | 98.9 | 71.2 | 10.2 |
| DE | 99.3 | 67.3 | 6.6 |
| DK | 99.6 | 98.7 | 30.6 |
| EE | 99.2 | 44.8 | 2.3 |
| EL | 93.6 | 29.6 | 2.8 |
| ES | 99.4 | 74.5 | 12.8 |
| FI | 99.7 | 63.0 | 5.0 |

| | | | |
|----|------|------|------|
| FR | 99.4 | 65.5 | 6.6 |
| HR | 92.5 | 19.0 | 0.4 |
| HU | 98.8 | 50.0 | 3.2 |
| IE | 99.6 | 47.2 | 4.1 |
| IT | 99.3 | 86.2 | 16.2 |
| LT | 99.0 | 44.6 | 3.1 |
| LU | 97.2 | 69.7 | 5.3 |
| LV | 99.4 | 33.8 | 1.7 |
| MT | 98.9 | 74.8 | 4.4 |
| NL | 99.5 | 96.8 | 26.6 |
| NO | 99.8 | 77.8 | 11.8 |
| PL | 98.4 | 55.1 | 6.2 |
| PT | 99.9 | 77.6 | 16.7 |
| RO | 94.6 | 43.8 | 1.8 |
| SE | 99.6 | 79.1 | 6.5 |
| SI | 96.7 | 14.0 | 0.5 |
| SK | 99.4 | 62.9 | 5.0 |
| UK | 99.7 | 86.6 | 16.4 |

Table A.4: FUAs with highest overall share (network share FRC0_5 x share with SP), population > 250k

| URAU_CODE | URAU_NAME | Network share FRC0_5 (%) | FRC0_5 share (%) | Share overall (%): Network share FRC0_5 x FRC0_5 share | Population |
|-----------|------------------|--------------------------|------------------|--|------------|
| UK017L2 | Cambridge | 51 | 91.66 | 46.34 | 355,915 |
| UK528L1 | Northampton | 48 | 93.70 | 44.90 | 451,113 |
| UK560L1 | Oxford | 48 | 90.08 | 43.52 | 517,390 |
| DE036L0 | Moenchengladbach | 45 | 95.31 | 42.89 | 255,362 |
| UK025L3 | Coventry | 44 | 94.65 | 41.23 | 555,157 |

| | | | | | |
|---------|------------------------------|----|-------|-------|-----------|
| UK014L1 | Leicester | 43 | 94.95 | 40.83 | 836,295 |
| CH002L2 | Geneve | 42 | 95.89 | 40.71 | 544,147 |
| UK033L1 | Guildford | 41 | 95.18 | 39.01 | 259,994 |
| DE011L1 | Duesseldorf | 40 | 97.04 | 38.45 | 1,502,208 |
| BE005L2 | Liege | 44 | 87.39 | 38.35 | 731,357 |
| DE546L0 | Wuppertal | 39 | 97.01 | 38.12 | 342,510 |
| DE542L1 | Hildesheim | 45 | 84.26 | 37.84 | 277,384 |
| UK002L3 | Birmingham | 39 | 96.93 | 37.62 | 2,862,495 |
| DE004L1 | Koeln | 39 | 95.56 | 37.54 | 1,894,716 |
| UK518L1 | Derby | 41 | 92.16 | 37.48 | 466,266 |
| DE507L1 | Aachen | 40 | 93.68 | 37.20 | 538,259 |
| DE548L1 | | 42 | 87.97 | 36.96 | 258,845 |
| CH005L2 | Lausanne | 39 | 95.17 | 36.83 | 382,523 |
| UK568L1 | Cheshire West and Chester | 41 | 86.03 | 35.60 | 481,186 |
| CH001L2 | Zurich | 36 | 98.94 | 35.58 | 1,242,916 |

Figure A.1: Share of FUA network that is FRCO-5

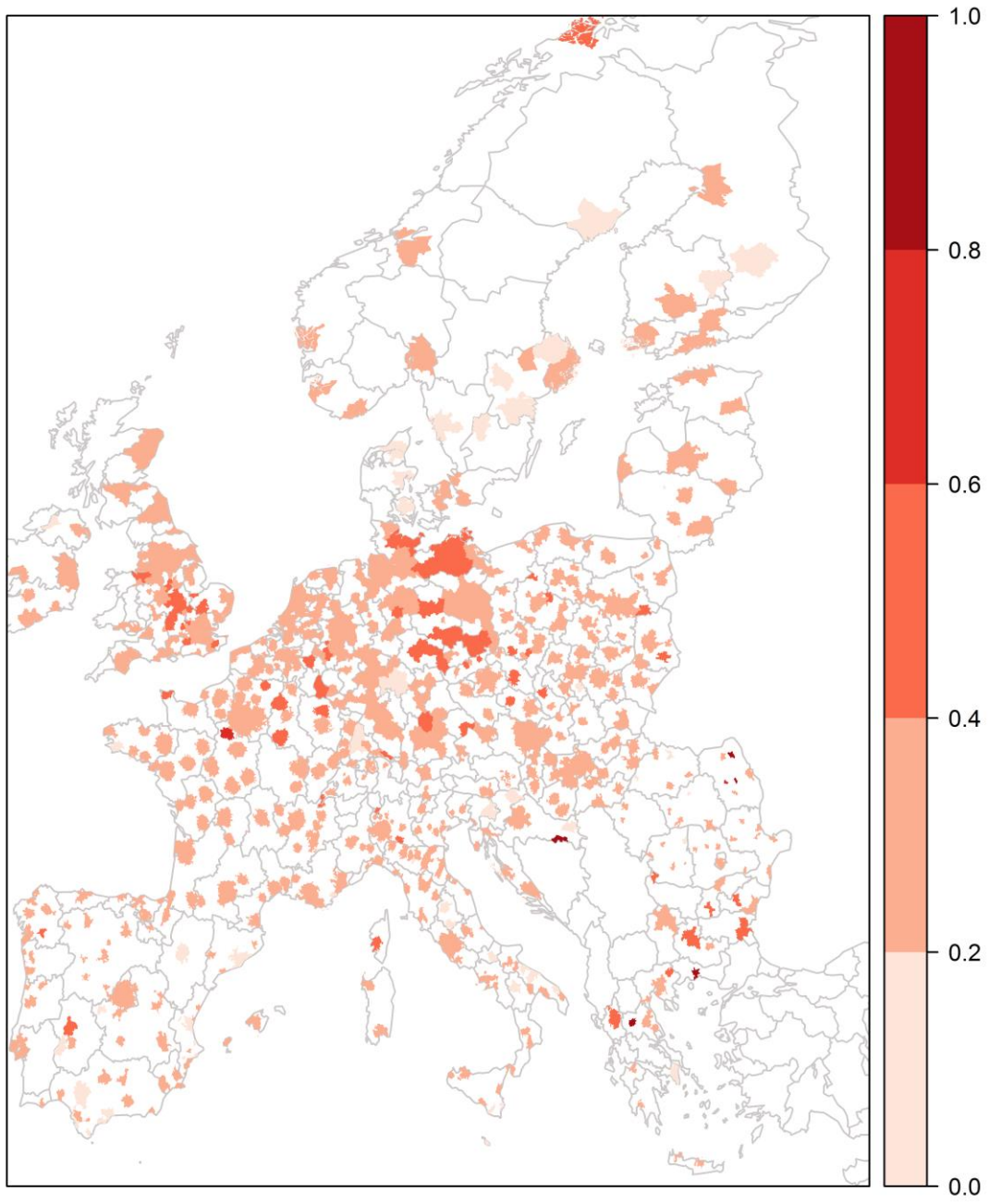


Figure A.2: Share of FRCO-5 links that have a speed profile

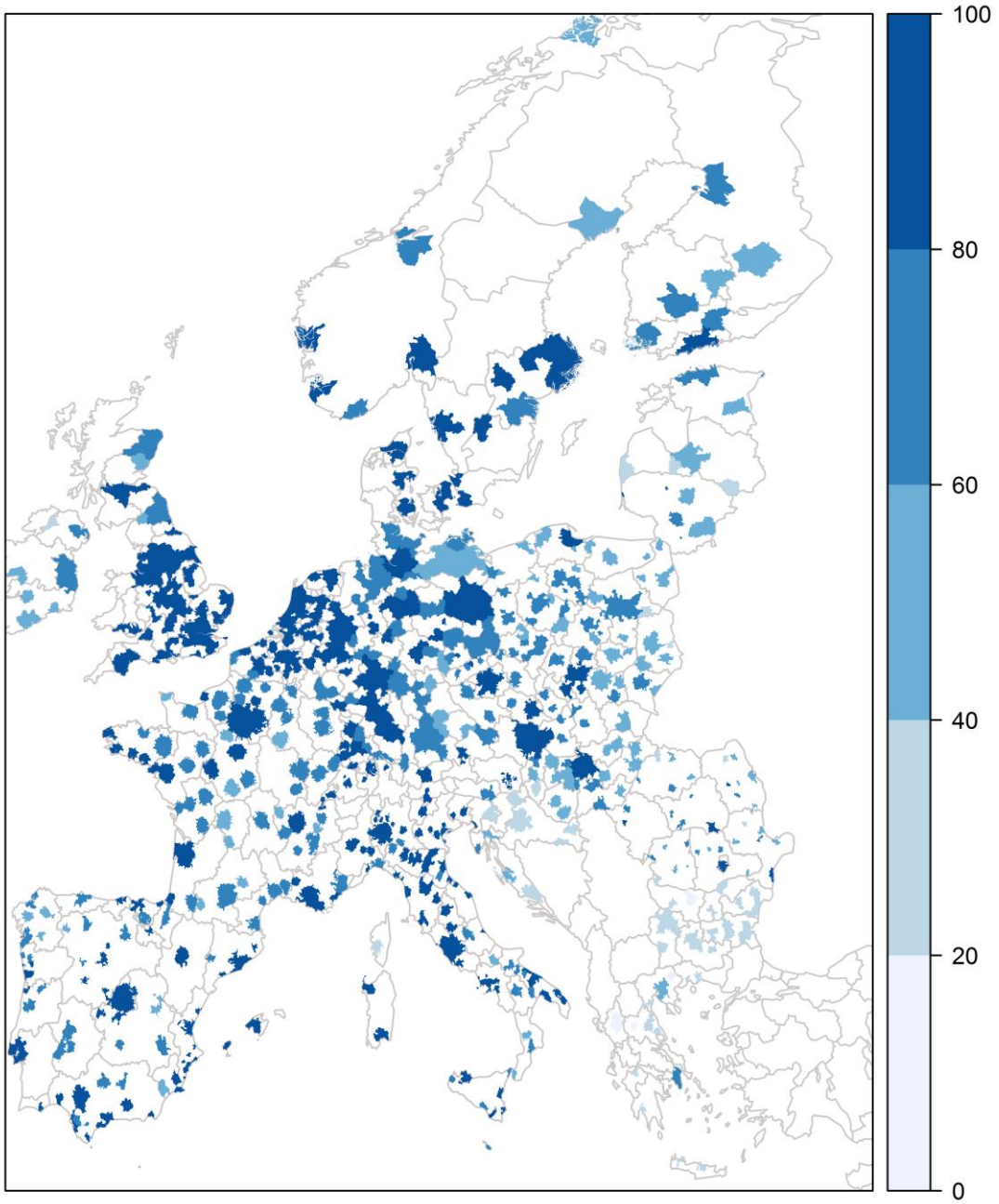
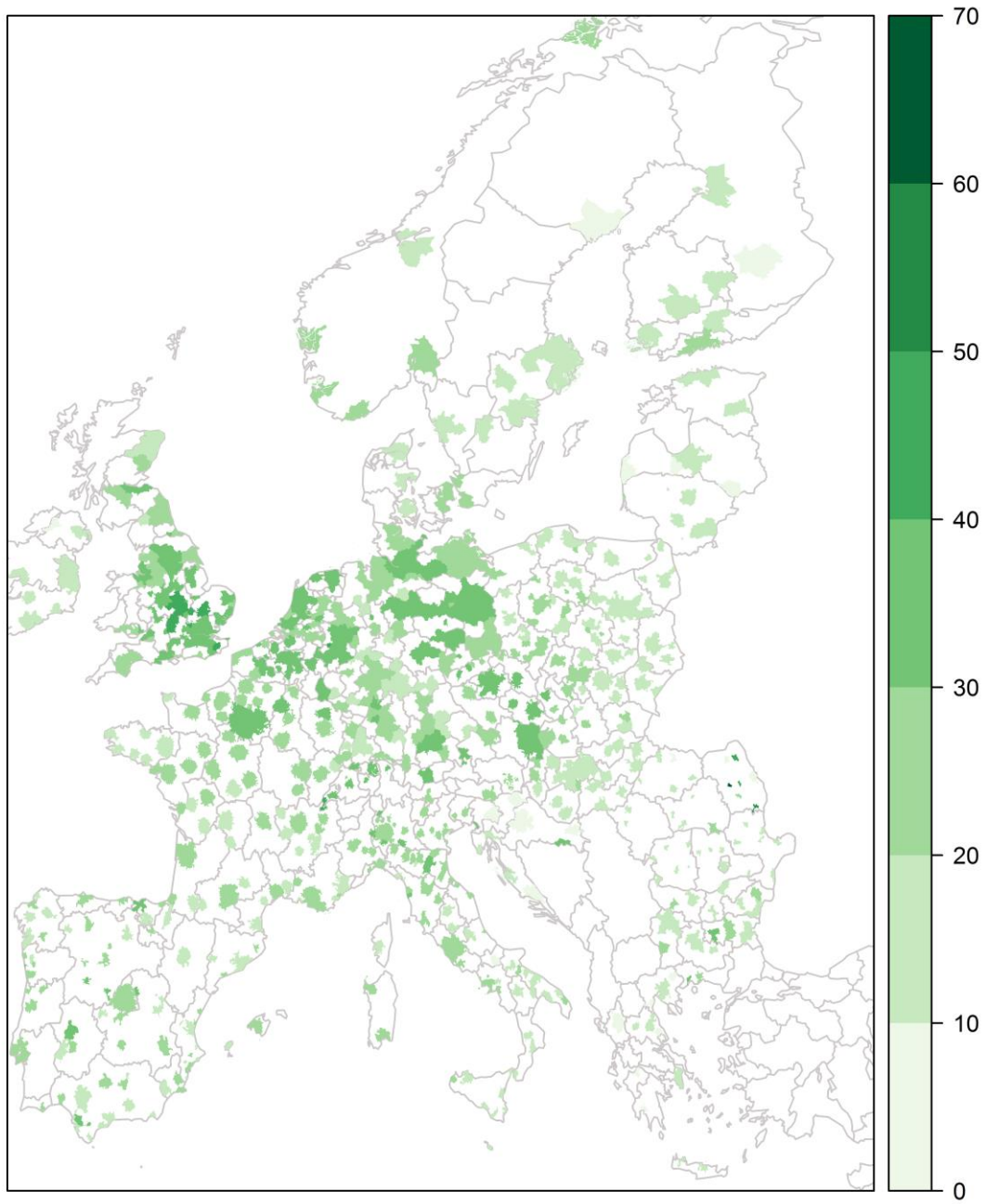


Figure A.3: Share of FRCO-5 with SP compared to total network



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