EJTIR

Issue 16(2), 2016
pp. 300-318
ISSN: 1567-7141
tlo.tbm.tudelft.nl/ejtir

# The impact of measuring internal travel distances on self-potentials and accessibility

**Ana Margarida Condeço Melhorado**[1]
Human Geography Department, University Complutense of Madrid, Spain

**Hande Demirel**[2]
Department of Geomatics Engineering, Istanbul Technical University

**Mert Kompil**[3]
European Commission, DG Joint Research Centre (JRC), Institute for Environment and Sustainability

**Elena Navajas**[4]
European Commission, DG Joint Research Centre – Institute for Prospective Technological Studies

**Panayotis Christidis**[5]
European Commission, DG Joint Research Centre – Institute for Prospective Technological Studies

Internal travel distances are fundamental in accessibility measurement, as they affect the weight of the intra-regional interactions, especially when using a gravity formulation. The contribution of the internal accessibility of each zone to its overall accessibility is known as self-potential. Several studies demonstrate its importance in accessibility analyses, especially in the most urbanized regions. It is precisely in urban regions where internal travel distances are more difficult to estimate due to congestion, which in turn may be influenced by factors such as urban density, urban morphology, network infrastructure, etc.

Accessibility analyses usually use coarse estimates of internal distances, generally based on the regions' area and in some cases considering its level of urbanization. In this study we explore different forms of estimating internal travel distances in accessibility analysis and reflect on their advantages and drawbacks. One of the main difficulties that arise when measuring internal travel distances is the lack of data. However, the growing potential of ICTs in providing new sources of data can be used to improve representativeness of data. In this study we used speed profiles data from TeleAtlas/TomTom to calculate internal travel distances for European NUTS-3 regions and we compare this measure with three other metrics traditionally used in the literature. Following this exercise, we discuss the conditions under which it is advantageous to use more complex measures of internal travel distance. Finally, we test the sensitivity of potential accessibility indicators to the combined effect of different internal distance metrics and distance decay factors.

***Keywords***: *accessibility, internal distance, self-potential, ICT*

---

[1] A: C/ Profesor Arangüren, s/n, 28040, Madrid, T: +34 913945727, E:acondeco@ghis.ucm.es
[2] Faculty of Civil Engineering, 34469, Maslak-Istanbul, Turkey, T: +90 2122856562, E: hande.demirel@itu.edu.tr
[3] A: Via E. Fermi, 2749, 21027 Ispra (VA), Italy T:+39 0332783952, E:Mert.KOMPIL@jrc.ec.europa.eu
[4] A:C/ Inca Garcilaso, 3, 41092 Seville, Spain, T:+34 954488266, E: elena.navajas-cawood@ec.europa.eu
[5] A:C/ Inca Garcilaso, 3, 41092 Seville, Spain, T:+34 954488266, E: Panayotis.CHRISTIDIS@ec.europa.eu

# 1. Introduction

Spatial interaction models have been applied to measure accessibility since the early years of regional science, starting with the work of Hansen (1959). He explored the relationship between accessibility and residential development in metropolitan areas, defining accessibility as "a possibility of interaction". His work was so influential that this measure is now commonly known as "Hansen's formula", but also as "Potential accessibility", "Market potential" (Harris, 1954) and "Economic potential" (Clark et al.1969). The potential accessibility of a location reflects its capacity to reach or to be reached by other locations such as markets or input sources, taking into account the distance to those locations.

The potential accessibility indicator has been applied for instance to evaluate changes in transport infrastructure (Linneker and Spence, 1996 Vickerman et al., 1999; Gutiérrez et al. 2010), access to services of general economic interest (Haynes, et al., 2003; Salze, et al. 2011; Paez, et al. 2010), to explain traffic flows (Simma, and Axhausen, 2003), as a factor of productivity (Head, and Mayer, 2004; Ottaviano and Pinelli, 2006), to describe the spatial distribution of economic activities (Holl, 2007, Paez, 2004) or to map population changes across space (Portnov et al, 2011), among other uses. The standard formulation is:

$$P_i = \sum \frac{M_j}{f(d_{ij})} , \tag{1}$$

Where $P_i$ is the potential accessibility of location i, $M_j$ is the mass associated with a destination location j and $f(d_{ij})$ is a function (f) representing the distance (d) between i and j.

When applying the potential accessibility measure, several decisions need to be taken which are not free of controversies, such as the demarcation of the study area, the unit of analysis, the variable that represents the mass of the destination location (i.e. population, GDP), or the variable to account for the distance (i.e. kilometres, travel time or generalized transport costs). Also the method to estimate distances, which goes from simple measures of straight-line and great circle distances, to more accurate ones such as distances along a transport network. Potential accessibility can be measured for a specific mode of transport or considering a combination of transport modes and it may be adjusted to represent freight or passenger traffic.

An important factor when measuring accessibility is the function of distance decay which may assume different forms, such as the power function (Hansen 1959), the exponential function (Wilson, 1971), the Gaussian (Ingram, 1971), or the log-logistic (Bewley and Fiebig, 1988).

Some studies have shown that the selection of the distance decay function greatly affects the outcome of the accessibility indicator (Baradaran and Ramjerdi, 2001; Reggianni et al., 2011b, Martínez and Viegas, 2013). The distance decay factor is introduced in the potential accessibility formula to better represent the relationship between the observed interaction patterns and distance. Highly negative parameters are interpreted as a strong deterrence factor for interaction. However not all studies include the calibration of this parameter (Gutiérrez et al., 2010) due to lack of data on flows within the study area.

Also well known in the literature is the role of self-potentials, which represent the part of spatial interaction that is intra-zonal rather than inter-zonal. Self-potentials are especially high in larger cities, giving their greater economic dynamism and have a significant contribution to the overall level of accessibility in those areas (Bruinsma and Rietveld, 1998, Frost and Spence, 1995). A correct specification of self-potential depends on the estimation of internal travel distances (measured as km, time or costs) that is the distance travelled within regions. Thus giving the weight of self-potentials on the level and distribution of accessibility, the decision on how to measure internal travel distance appears as crucial. However internal travel distances are difficult to be determined and are commonly estimated based in coarse assumptions, due to the lack of data, about transport networks and flows within regions. Only a few studies were found to explore the different methods to estimate internal travel distances (Rich 1980, Owen and

Coombes, 1983; Frost and Spence, 1995). Furthermore when different internal travel distances are tested, only less accurate methods are compared (Rich 1980, Owen and Coombes, 1983; Frost and Spence, 1995).

In this study we will contribute to this branch of literature by analysing the impacts of choosing different internal travel distance specifications (measured in terms of internal travel time) and contrasting more arbitrary methodologies with more realistic approaches. In this sense we will give a step forward in the measurement of internal travel distances by linking information from ICT (Tele Atlas/TomTom database) to network analysis methodologies.

The impact of choosing different internal distance metrics is expected to increase with higher negative distance decay factors, since short distance relationships and thus self-potentials, will have a higher weight on the final accessibility levels. We test this hypothesis by taking the combined effect of changing internal distance measures and using a calibrated distance decay factor into account. To the best of our knowledge this is the first time the combined effect of calibrating or not the distance decay factor and changing internal travel distance measure is analysed.

The next section emphasizes the role of internal travel distances and the calibration of distance decay in self-potentials and critically reviews several methods used in the literature to estimate internal travel distances. Section 3 and section 4 describe the data and explain the methodology followed to test several measures of internal travel distances. Results are presented in section 5 and conclusions are drawn in the last section of the article.

## 2. Self-potential, internal travel distance measures and distance decay factor

As briefly presented in the introduction section, several studies use the potential accessibility indicator but only a few reflect on the way to measure internal travel distances. This, however, may have an important impact on the final outcome. The reason lies on the mathematical formulation which tends to give higher weights to closer spatial interactions.

The way internal travel distances are measured determines the contribution of the self-potential on the overall accessibility levels of a zone. Self-potentials (SP) would be a subset of equation 1, representing the potential interaction with local markets and could be formulated as:

$$SP_i = \sum \frac{M_i}{f(d_{ii})}, \qquad (2)$$

Frost and Spence (1995) have shown that the contribution of self-potential is especially high in big cities. For London they have measured a contribution of self-potential that was around 60% of its overall potential accessibility. Omitting the self-potential would lead to lower accessibility values for larger regions and higher potential accessibility for small regions close to larger ones.

A more precise estimation of self-potential depends on the measurement of internal travel distances. Smaller internal travel distances would lead to a higher contribution of self-potentials. But this change would not be uniform across regions, Frost and Spence (1995) concluded that this impact was higher for the most important regions as well as for the most isolated ones. Thus changing the internal distance measure does not only imply a change in the accessibility values but also changes in the spatial distribution of accessibility levels.

Distance decay on the other hand represents the level of resistance to movement of a given location. Higher negative values reflect less proneness to travel towards distant destinations, which results in a higher importance of local markets and consequently in a higher role of self-potentials. Condeço-Melhorado et al. (2013) have shown that the role of self-potential increases with high values of distance decay, since the interaction with distant locations have a lower weight on accessibility levels. From their results we can assume that the measurement of internal travel distance deserves more importance when high distance decay factors are in place, since access to intra-zonal activities will weight relatively more than interregional ones.

Correctly estimate internal travel distances at regional level is difficult due to the lack of data. Ideally it could be derived from regional travel surveys, but in practice these are rarely available. For this reason many studies have developed methods to estimate internal travel distances (length, travel time or GTC) which can be classified as (see also Table 1):

- Area based: One of the most frequently used approaches is inspired in Stewart's work (1947). He estimated internal travel distances by representing the region as a circle of equivalent area and using a transformation of the radius (r) of that circle, suggesting the use of 0.5r. Frost and Spence (1995) found that the transformation of 0.5r represents a situation where population is evenly distributed within the region (Frost and Spence, 1995). Other authors used smaller values of radius transformation, suggesting that this would better represent the peaking of population towards the centre of the zone (Rich, 1978, Owen and Coombes, 1983, Dundon-Smith and Gibb, 1994). Comparing the region with a circle is controversial and some authors use a modified version of the formula that accounts for the shape of the area (Kotovaara et al, 2011) while others prefer to estimate internal travel distances by using directly the area of a zone (van Wee, et al. 2001). Area based methods rely on two main controversial assumptions, 1) regions are represented as if they were monocentric, while many regions contain several cities that attract and generate trips between each other and 2) it considers distances measured as straight lines from the centre to the border, without taking into account the existing transport networks.
- Fixed values: the same internal travel distance is added to the diagonal of the distance matrix to allow for intra-zone effects (Anderson, 1956, Houston, 1969, Reggiani, et al. 2011a). This method is less precise, since it does not account for the size of the regions or their congestion level. It can also be argued that the selected values are somehow arbitrary.
- Density based measures: measures that directly relate the level of agglomeration of population and/or economic activity existing within a region, with its internal travel time (Gutiérrez, 2001; Baradaran and Ramjerdi, 2001). Density based measures are a better proxy for the congestion levels of regions, since the higher the agglomeration of population and economic activity in a region, the higher its congestion level. However these measures are not able to differentiate the characteristics of existing transport infrastructure, which may differ between regions with similar levels of urban density.
- Point-to-point distances: internal travel distances are (weighted) average distances between zones within a region. Handy (1993) uses the inter-zonal, rather than the intra-zonal distance and then corrects by an observed trip length frequency distribution. This measure seems somewhat arbitrary since it largely depends on the location of the three closest neighbours; Östh et al. (2014) consider a very detailed set of locations within regions, however they compute distances in straight line, without considering the quality of networks. Ottaviano and Pinelli (2006) offer a precise measure of internal travel distance, considering both the locations and the network within the region. In general this method seems to be a relatively good approach in the absence of more precise data (e.g. travel surveys), avoiding the assumption of a monocentric region by considering the interaction between different centres within a region. Furthermore these measures are able to account for distances along the transport network which may differ in terms of the regional endowments and congestion levels.
- Data from travel surveys: this data is usually collected for a given area, including relevant information such as trip length, frequency, trip purpose, etc. (Levinson 1998). This is the most appropriate data to represent internal travel distances, coming directly form observed/declared mobility patterns, which better reflects real traffic flows in a network.

These data are usually available for bigger metropolitan regions, but this is rarely available for less urbanized regions.

**Table 1. Classification of internal travel distance measure**

| Classification of internal travel distance measure | Formulation | | References |
|---|---|---|---|
| *Area based* | $Dii = x\sqrt{\frac{area\ of\ the\ region}{\pi}}$<br>Dii is the internal distance<br>x is the transformation of the radius (r) that differs among authors | (3) | x ranges from 0.33r to 0.5r in Rich (1978; 1980);<br>from 0.25r to 0.5r in Owens and Coombes (1983)<br>from 0.33r to 1r in Frost and Spence (1995)<br>x equal 0.33r in Dundon-Smith and Gibbs (1994)<br>x equal 0.5r in Condeço-Melhorado at al. (2011) |
| | $Dist_i = \left(2 * \sqrt{area_i}\right) / 3$<br>Where $\text{Dist}_i$ is the internal distance for zone i, $\text{area}_i$ is the area of zone i | (4) | van Wee et al. (2001), these authors then use an average travel speed of 33 m/h to translate internal km into internal travel time. |
| | $d_{ii} = \left(1 + ln\left(\frac{perimeter/2\pi}{\sqrt{(area/\pi)}}\right)\right) * \frac{\sqrt{\left(\frac{area}{\pi}\right)}}{\sqrt{2}}/speed$<br>Area based measure corrected by the difference between the shape of the region and the circle | (5) | Kotovaara et al. (2011)<br>Speeds = 40 km/h |
| Density based | $T = 15 * \log(P * 10)$<br>Where T is the internal travel time of a region and P is its population. | (6) | Gutiérrez (2001) |
| | $t_{ij} = \frac{d/4}{40};$<br>where $d = \frac{\sqrt{O/\pi}}{2};$<br>where $O = \frac{Population}{Density}$ | (7)<br>(8)<br>(9) | Baradaran and Ramjerdi (2001) |
| *Fixed values* | 10 and 20 minutes | | Reggiani et al. (2011a) |
| *Point-to-point distances* | Own distances dii are weighted average distances along the road network between NUTS 5 centres within each NUTS 4 region (as defined by the authors). Size is measured by aggregate income. | | Ottaviano and Pinelli (2006) |
| | Average travel time to the three closest zones, adjusted by the trip length distribution for shopping trips | | Handy (1993) |
| | Distance between home – work locations | | Östh et al. (2014) |
| *Travel surveys* | e.g. household travel survey for Metropolitan Washington | | Levinson (1998) |

## 3. Data

In order to draw conclusions about the possible impacts of different internal distance metrics on accessibility results, we performed a sensitivity analysis for a set of regions. Accessibility was calculated for NUTS-3 regions in the EU-27 where the capital of the country is located[6]. This selection of the study area has two main advantages: we reduce the complexity of the exercise, while ensuring that regions with higher self-potential are represented in the analysis. These regions are expected to be more sensitive to the measure of internal travel time, as was discussed in section 2. Regional GDP data was collected from Eurostat[7].

For this study the location of population settlements inside each region was derived. This data was elaborated by processing a European raster dataset containing the population counts by 1 $km^2$ grid cells[8]. We have processed this data using the following steps:

- Grids having population higher than or equal to 10000 in the studied NUTS3 regions were selected via SQL query. These selected grids were used as the dispersed urban areas within the NUTS3 regions.
- These grids were generalized in order to create areas that share similar characteristics by means of the majority filter, which is also known as binary median filter (Huang et al., 1979) often used in digital image processing. This methodology replaces cells in a raster based on the majority of their contiguous neighbouring cells, where the number of neighbours used for these analyses was eight. This generalization process resulted in several urban zones within each NUTS3 region.
- In order to represent these settlements, centroids were created from the derived intra-NUTS3 zones.

The TRANS-TOOLS [9] road network was used to estimate travel time between NUTS 3 regions. The network covers all European countries[10] and includes the main European roads and ferry connections. From the attributes contained in the road network, free speed was particularly useful to calculate the travel time between NUTS-3 regions

As mentioned earlier, one of the novelties of this study is the use of data retrieved from ICT data sources to calculate internal travel times. As highlighted in previous studies, ICT data can provide a good input to accessibility indicators (van Wee et al., 2012). Data from Tele Atlas/TomTom was used for the extract of speed profiles that were introduced to the TRANS-TOOLS road network for the calculation of internal travel times. This process requires long computation times, for this reason it was only performed within the NUTS-3 regions.

## 4. Methodology

We calculate accessibility with the market potential indicator:

$$A_i = \sum_{j=1}^{n} \frac{m_j}{t_{ij}^{\beta}} \tag{3}$$

Where Ai refers to the accessibility of zone i, m refers to the economic attractiveness of destination zone j, which we considered as regional GDP. Zones are represented by the centroid of the NUTS-3 region. On the denominator side, t is the time of travel between an origin and a

---

[6] Romania and Bulgaria are excluded due to lack of data on ICT and Cyprus and Malta are excluded due to lack of road network data

[7] According to Eurostat, the overall accuracy of regional GDP data varies according to the region size; it is lower for small, sparsely populated regions, which is not the case of the capital regions selected in this study.

[8] The European Population dataset was produced by The GEOSTAT project and supported by Eurostat within the Framework of the ESSnet program. (http://epp.eurostat.ec.europa.eu/portal/page/portal/gisco_Geographical_information_maps/geostat_project, accessed in 04/12/2013)

[9] http://energy.jrc.ec.europa.eu/transtools/

[10] Except Cyprus and Malta

destination and β is a distance decay parameter that is calibrated to represent the friction of movement.

The distance decay parameter was initially calibrated for both of the power and the exponential cost functions. They were recorded as 2,5 for power and 0,027 for exponential decay functions. Since the power cost function fitted the observed interactions better, i.e., it has less standardized root mean square error, less mean travel cost error and higher r square, it was decided to use the distance decay parameter in the form of power cost function. This is also consistent with other studies showing that the power function is more appropriate for long-distance trips (Reggiani et al, 2011b) as it is the case of this study. The calibration was achieved based on the Wilson's (1967, 1970) doubly constrained gravity model form, using maximum likelihood estimation. A description of the maximum likelihood estimation method, which maximizes the likelihood function of a theoretical Poisson distribution of interactions can be seen in Sen (1986) and Fotheringham and O'kelly (1989). The observed trip interactions between the 23 capital regions were used as input for the calibration. They are derived from the TRANS-TOOLS road passenger baseline trip matrix (2005).

Travel time between regions can be estimated with the standard network analysis tool available in Geographical Information Systems. Dijkstra's algorithm (Dijkstra, 1959) was used for the estimation of travel times between zones. As in Condeço-Melhorado et al. (2011), we assume additional travel time for each NUTS-3 region corresponding to access and egress time, since most of the trips do not start in the centroids of the origin and destination regions. Total travel times between zones were then computed as:

$$TT_{ij} = p_i + tr_{ij} + p_j \tag{4}$$

Where TT represents the travel time between an origin and destination regions, tr is the travel time along the route of minimum travel time and p is the extra time for leaving and entering NUTS-3 regions. This extra time is equivalent to half of the internal travel time of the respective NUTS-3 region.

As argued in the previous sections, the accessibility level of a region can be very sensitive to the methods used for the estimation of internal travel times. In this paper we test four different approaches for measuring internal travel times and explore whether they lead to significantly different results. The internal travel time methods to be tested are:

Approach A – Fixed value of travel time: we assume 20 minutes of travel time within all NUTS-3 regions.

Approach B - Area based: this approach is simply based on the zone size. It calculates the average travelled km within a region, using the formula (equation 12) proposed by Rich (1978). Internal travel time is then estimated assuming the same travel speed of 50 km/h for all regions.

$$D_{ii} = \frac{1}{2}\sqrt{\frac{area}{\pi}} \tag{5}$$

Approach C - Area based combined with Tele Atlas/TomTom data. This approach uses equation 12 for the estimation of average travelled Km within a zone. Tele Atlas/TomTom travel speeds of links within a region were averaged following equation 13. Finally, internal travel times were estimated for each region using its average travel kilometres and average travel speed.

$$\bar{X}TS_i = \frac{\sum_{l\in i}^{n} TS_l * Km_l}{\sum_{l\in i}^{n} Km_l} \tag{6}$$

Where l represents a road network link, TS means travel speed, and Km the kilometre of link l.

Approach D - Point-to-point travel times. Average travel time within a zone is calculated based on point-to-point travel times, where points are population centroids coming from the population grid described earlier. Travel times between these points are calculated using the road network containing travel speeds extracted from Tele Atlas/TomTom. Then average travel time for each NUTS-3 region is estimated using the population of origin and destination centres as weights, following formula 14:

$$\bar{X}_w TT_i = \frac{\sum_{c\in i}^{n} \bar{X}_w TT_c * P_c}{\sum_{c\in i}^{n} P_c} \tag{7}$$

$$\bar{X}_w TT_i = \frac{\sum_{c\in i}^{n} TT_{cd} * P_d}{\sum_{d\in i}^{n} P_d} \tag{8}$$

TT is the travel time along the network that has been calculated using the Dijkstra's algorithm, as previously i represent the NUTS-3 of origin, while the subscripts c and d represent the population centres of origin and destination within a zone, respectively and P represents their population.

For simplicity reasons previous approaches are called approach A, B, C and D in the rest of the paper. It is assumed that approach D gives more realistic results than other approaches since both networks and population centres are considered for the estimations of internal travel times (see Figure 1). Approach C on the other hand is assumed to be more accurate than approach B since it introduces the average travel speeds from Tele Atlas/TomTom data which differ according to the region. The less accurate approach in our view would be A which assumes the same travel time for all regions independently of their size, quality of transport networks and the location of the population settlements.

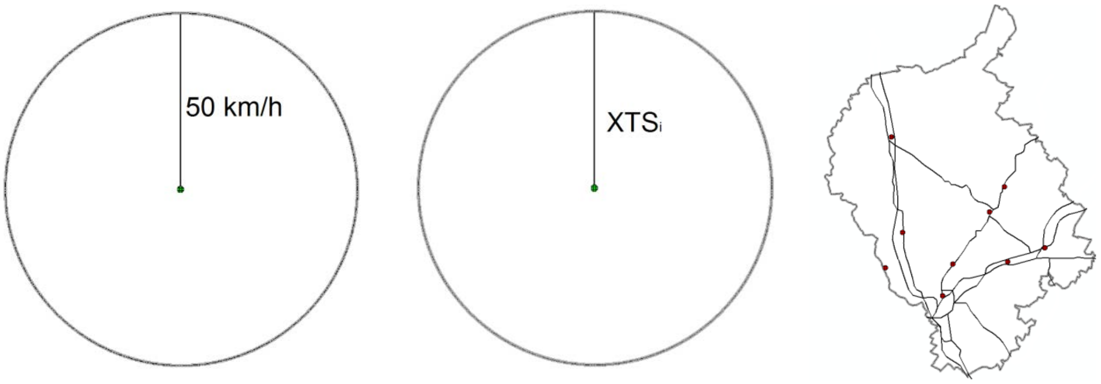

*Figure 1. Graphical comparison between approaches B, C, and D (from left to right)*

## 5. Results

Since the complexity and costs increase from approach A to D the first question addressed in this section is whether the effort of increasing the accuracy of measurement is really worth in terms of improving the quality of the results. We do this by observing whether the four approaches produce significantly different results. We explore how the regional characteristics are reflected in the assumptions underlying the different internal distance measures. To test the hypothesis described in the beginning of the paper, we continue our analysis by analysing the impact of different internal travel time metrics in the accessibility levels of regions. We focus on accessibility rankings however absolute accessibility values are also presented in Appendix A.

Finally we test whether the inclusion of a calibrated distance decay factor in the market potential indicator leads to higher variations of the accessibility levels using different measures of internal travel time.

### *5.1 Comparing different internal travel time metrics*

Table 2 shows the internal kilometres, the average internal travel speed and the internal travel time calculated with the four different approaches presented in the previous section. The first two columns refer to internal kilometres of approaches B and C (first column) which compare the region with a circle of the same area and assume that the whole of the population is located in a central point. Approach D on the other hand considers that population is more or less spread out in different centres within a region and that travel between those centres is measured using a road network. Results show that D generally entails higher estimates of internal kilometres and suggests that previous approaches underestimate internal travelled kilometres when assuming the population is concentrated in a centre and trips are performed in straight line from the centre to the border of the region.

**Table 2 – Distance measures within NUTS-3 regions**

| | *Internal Km* | | *Internal Speed* | | *Internal Travel time* | | | |
|---|---|---|---|---|---|---|---|---|
| Name | Km(B, C) | Km (D)[11] | Speed (C) | Speed (D) | min (A) | min (B) | min (C) | min (D) |
| Vienna | 5.7 | 21.4 | 43.2 | 27.6 | 20 | 6.9 | 8.0 | 46.5 |
| Brussels | 3.6 | 6.5 | 27.2 | 33.9 | 20 | 4.3 | 7.9 | 11.5 |
| Prague | 6.3 | 14.1 | 40.5 | 26.4 | 20 | 7.5 | 9.3 | 32.0 |
| Berlin | 8.4 | 21.3 | 30.5 | 24.9 | 20 | 10.1 | 16.6 | 51.5 |
| Copenhagen | 3.8 | 9.9 | 34.9 | 22.0 | 20 | 4.6 | 6.5 | 27.0 |
| Tallinn | 18.6 | 13.3 | 65.8 | 28.6 | 20 | 22.3 | 16.9 | 28.0 |
| Madrid | 25.3 | 28.9 | 61.4 | 33.2 | 20 | 30.3 | 24.7 | 52.2 |
| Helsinki | 23.1 | 34.4 | 59.7 | 30.9 | 20 | 27.8 | 23.2 | 66.7 |
| Paris | 2.9 | 10.2 | 31.3 | 33.3 | 20 | 3.5 | 5.6 | 18.4 |
| Athens | 17.4 | 26.1 | 55.8 | 24.2 | 20 | 20.9 | 18.7 | 64.8 |
| Budapest | 6.5 | 21.3 | 47.8 | 27.5 | 20 | 7.8 | 8.1 | 46.5 |
| Dublin | 8.6 | 23.6 | 39.0 | 24.2 | 20 | 10.3 | 13.2 | 58.5 |
| Roma | 20.6 | 37.4 | 48.4 | 22.4 | 20 | 24.8 | 25.6 | 100.3 |
| Vilnius | 27.8 | 23.3 | 65.6 | 35.6 | 20 | 33.4 | 25.5 | 39.4 |
| Luxembourg | 14.4 | 20.8 | 55.2 | 33.8 | 20 | 17.2 | 15.6 | 36.8 |
| Riga | 4.9 | 7.4 | 35.7 | 24.9 | 20 | 5.9 | 8.3 | 17.8 |
| Amsterdam | 8.4 | 24.3 | 46.9 | 34.1 | 20 | 10.1 | 10.8 | 42.8 |
| Warsaw | 6.4 | 15.9 | 32.7 | 27.8 | 20 | 7.7 | 11.8 | 34.3 |
| Lisbon | 10.4 | 28.1 | 43.8 | 21.3 | 20 | 12.4 | 14.2 | 79.2 |
| Stockholm | 23.8 | 36.1 | 54.7 | 25.4 | 20 | 28.5 | 26.1 | 85.3 |
| Ljubljana | 14.3 | 25.9 | 76.0 | 41.7 | 20 | 17.1 | 11.3 | 37.3 |
| Bratislava | 12.8 | 21.2 | 56.6 | 27.0 | 20 | 15.3 | 13.5 | 47.1 |
| London | 2.9 | 8.7 | 29.6 | 28.5 | 20 | 3.5 | 6.0 | 18.3 |

(a), (b), (c), (d) refer to approach A, B, C and D

The use of average internal travel speed obtained from Tele Atlas/TomTom (as in C) represents and improvement of approach B, which assumes that all regions have the same travel speed (50km/h). On the other hand, C results in higher average travel speeds when compared with approach D. Travel speeds of approach D cannot be directly derived, because they are associated with network links, thus depending on the routes used for the connection between population

---

[11] Internal travelled kilometres can be automatically derived from the routes of minimum travel time between centres. These were again averaged for each region in the same fashion as in equation13

centres. Nonetheless for illustrative purposes, an average value for each region can be obtained from the information on internal travelled kilometres and internal travel times. Lower travel speed when using D implies that when routes along a network are considered, congested roads have a higher weight on the final result.

Internal travel times are presented in the last four columns of Table 2. A fixed value of internal travel time, as in A, overestimates the one of smaller regions and underestimates the internal travel time of larger regions, especially when A is compared with area-based approaches (B,C). These differences increase when approach A is compared with D, usually resulting in higher underestimations. However approaches A and D present more similar results in small and urbanized regions, were the effect of congestion increases their internal travel time as measured with D.

In approach B internal travel time only depends on the area of the region (first column), as we assume the same travel speed for all regions (50 km/h). As a result, bigger NUTS 3 regions have higher internal travel times as it is the case of Vilnius, Madrid or Stockholm (see also table A1 in Appendix A).

Approach C on the other hand takes into account different travel speeds between NUTS-3 regions. This can be considered as a proxy for congestion level, with more congested regions having lower average travel speeds. This is the case of Brussels, London, Berlin or Paris, where Tele Atlas/TomTom data revealed average speed profiles around 30 km/h. For these regions it is clear that approach B underestimates their internal travel time while the opposite occurs for less congested regions as Ljubljana, Tallinn or Vilnius.

Since approach D gives higher values of internal travelled kilometres and lower values of internal travel speeds than B and C, it comes with no surprise that higher internal travel times are estimated when D is applied. We also tested whether internal travel time measures are significantly differ from each other. Results show that the mean absolute difference between travel time measures significantly differs from zero at 95% confidence interval. Mean absolute differences between approaches B and A, C and A and D and A is respectively 9.7, 7.9 and 26.5 minutes and mean absolute differences between approaches C and B, D and B and D and C is respectively 3.0, 29.9 and 30.3 minutes. The difference is more visible when expressed in percentages. The mean absolute difference, for instance, between B and A, C and B, D and B and D and C is 48.6%, 29.0%, 279.6% and 234.2% respectively.

From the analysis of previous results we may conclude that higher differences between point-to-point distance (D) and fixed distance approach (A) come mainly from the different size of the regions, as larger regions present higher underestimations of travel time measured with approach A. Differences between D and area-based approaches (B, C) are expected to be higher in regions were population is more spread out, since B and C assume that population is concentrated in a centre. We also expect that in regions with higher congestion levels, approach D will give results that are significantly different from other approaches, since congestion is better represented when applying D. Finally differences between approach D and other approaches may arise due to the fact that D uses the road network to estimate internal travel times while A do not consider the network differences between regions and B and C use crow-fly distances. In order to test these hypotheses we have correlated the differences between approach D and A, D and B and D and C (measured in percentage and converted into positive values) with four measures representing:

1. The area of the region, in squared kilometres.
2. The agglomeration of population centres on the region's centroid. This was estimated for each region as the average distance from each population centre to the centroid of a region, normalized by the area of the region. Higher values represent higher dispersion of population centres.

3. The average speed obtained from Tele Atlas/TomTom data for each region, estimated using equation 13.
4. The density of the network.

Results show that all four variables tested are significantly correlated with differences in travel time between D and B, but not with the D and C (Table 3). The positive correlation between the D – A differences and the area of the region is non-significant. Surprisingly it was only negatively correlated with the agglomeration measure (average distance to centroid).

On the other hand the correlation between D - B differences and the area of the region was negative and significant, meaning that the smaller the region the higher the differences in travel time estimates between both approaches. More interesting is the positive correlation between the agglomeration measure and the differences in D and B, which confirms that the less population centres are agglomerated around the centroid of the region (higher average distance to centroids), the higher the difference in internal travel time between D and B. Regarding congestion levels is also confirmed as being correlated with bigger differences between approaches D and B, lower average speeds lead to higher differences in travel time estimates[12]. Finally the density of the network appears as positively correlated with the differences in travel time estimates between D and B, which means that using crow-fly distances leads to a higher bias, especially in regions with a high network density.

In conclusion these results suggest that a more detailed measure of internal travel time (as approach D) should be preferred in regions with more dispersed population centres (polycentric urban structure), with higher congestion levels and in regions with higher endowments and complexity of transport infrastructure.

**Table 3. Correlation between differences in travel time measures and zones characteristics**

| Zone characteristics | | Difference between D and A (%) | Difference between D and B (%) | Difference between D and C (%) |
|---|---|---|---|---|
| *Area (km$^2$)* | Pearson Correlation | 0.393 | -.722** | -0.388 |
| | Sig. (2-tailed) | 0.063 | 0 | 0.067 |
| | N | 23 | 23 | 23 |
| *Average distance to centroid measure* | Pearson Correlation | -.678** | .564** | 0.157 |
| *Average Speed from ICT data* | Pearson Correlation | 0 | 0.005 | 0.475 |
| | Sig. (2-tailed) | 0.269 | -.695** | -0.166 |
| | N | 23 | 23 | 23 |
| *Density of Network* | Pearson Correlation | 0.214 | 0 | 0.449 |
| | Sig. (2-tailed) | -0.314 | .562** | 0.152 |
| | N | 23 | 23 | 23 |

**. Correlation is significant at the 0.01 level (2-tailed).

### *5.2 Impact of different internal travel time metrics and distance decay factor on accessibility levels*

Table 4 compares the accessibility results measured with different internal travel time metrics, showing a rank of regions ordered from the most to the less accessible one. The same table but with accessibility levels can be found in Appendix A (table A2).

This ranking may be biased up to a certain extent since we are using a very restricted set of regions, but it is useful to compare the stability of accessibility values when considering different internal travel time measures.

---

[12] This correlation was also tested for the average speed obtained from approach D leading to similar conclusions; the main exception was that it becomes significant with the ratio of travel time D / C.

The first four columns show the accessibility of each region using different measures of internal travel time. In all cases the accessibility indicator was calculated without calibrating the distance decay factor (β=1). Focusing on the results for approaches B, C and D, we observe that despite the variations in terms of internal travel time, the first and last positions of the accessibility ranking remain quite stable under all approaches. London, Paris, and Brussels are the most accessible regions while Riga, Tallinn and Vilnius appear in the lower part of this ranking. In between these regions, the selection of the internal travel time measure has a higher impact on the accessibility ranking. Regions such as Roma, Lisbon or Stockholm, where approach D gives significantly higher estimates than other distance metrics, rank higher decreases in the accessibility positions. Approach A reveals higher variations on the accessibility outcomes, improving the position of larger regions such as Madrid and Rome. As we have previously observed this coarser approach underestimates the internal travel times of larger regions, which in turn improves the role of their self-potential (see tables A3 in Appendix A) and consequently their accessibility level.

The statistical tests imply that the accessibility measures using the four approaches significantly differ from each other. When all accessibility values are scaled into the same interval, the mean absolute differences between each accessibility measures A, B, C and D significantly differs from zero, at 95% confidence interval.

The introduction of a calibrated distance decay factor into the accessibility equation showed a higher sensitivity of the accessibility ranking to the selected measure of internal travel time. Using a fixed travel time benefits even more the ranking position of larger regions, especially the ones with higher self-potential, as Madrid. Comparing the accessibility ranking achieved with approaches B, C, and D we observe a higher variation that now affects the first and last positions. The most affected regions are again the ones where approach D presents higher overestimates in terms of internal travel time, reducing the weight of self-potentials (see tables A3 in Appendix A), as it is the case of Rome or Lisbon that are now placed at the bottom of the table.

From these results we can conclude that the decision on the internal travel time measure affects the distribution of accessibility values, especially when using calibrated distance decay parameter.

Another interesting conclusion indirectly coming out from the results is that the size of NUTS 3 regions seems to have an important effect on the accessibility ranking. Comparing the accessibility ranking with and without calibrating the distance decay (Table 4) with approaches B, C and D, we observe an increase of accessibility position for small regions (e.g. Warsaw, Prague or Riga) with higher distance decay factors, even though the same distance metric is used. This is due to the role of self-potential that is high in small NUTS-3 regions, since by definition their GDP is more concentrated. This is also in line with Condeço-Melhorado et al. (2013) who found that regions with low self-potential lose more accessibility when using higher distance decay values, because they depend more on interactions with distant neighbours.

**Table 4. Accessibility rankings**

| **Accessibility ranking of regions β=1** | | | | **Accessibility ranking of regions β=2.5** | | | |
|---|---|---|---|---|---|---|---|
| *A* | *B* | *C* | *D* | *A* | *B* | *C* | *D* |
| Paris | Paris | Paris | Paris | Madrid | Paris | Paris | Brussels |
| Madrid | London | London | London | Paris | London | London | Paris |
| London | Brussels | Brussels | Brussels | London | Brussels | Vienna | London |
| Roma | Vienna | Vienna | Madrid | Roma | Copenhagen | Brussels | Copenhagen |
| Berlin | Berlin | Amsterdam | Amsterdam | Athens | Vienna | Copenhagen | Madrid |
| Brussels | Copenhagen | Madrid | Luxembourg | Stockholm | Berlin | Budapest | Riga |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Amsterdam | Amsterdam | Berlin | Berlin | Berlin | Warsaw | Amsterdam | Warsaw |
| Stockholm | Warsaw | Copenhagen | Vienna | Vienna | Prague | Prague | Prague |
| Vienna | Prague | Budapest | Prague | Amsterdam | Budapest | Dublin | Amsterdam |
| Athens | Dublin | Prague | Copenhagen | Brussels | Amsterdam | Warsaw | Vienna |
| Luxembourg | Madrid | Athens | Bratislava | Helsinki | Dublin | Berlin | Luxembourg |
| Dublin | Budapest | Dublin | Warsaw | Dublin | Riga | Lisbon | Berlin |
| Prague | Roma | Roma | Budapest | Lisbon | Lisbon | Athens | Athens |
| Helsinki | Athens | Luxembourg | Ljubljana | Warsaw | Athens | Madrid | Budapest |
| Budapest | Luxembourg | Warsaw | Roma | Copenhagen | Roma | Riga | Dublin |
| Warsaw | Lisbon | Stockholm | Dublin | Luxembourg | Madrid | Luxembourg | Tallinn |
| Bratislava | Stockholm | Lisbon | Athens | Prague | Luxembourg | Roma | Bratislava |
| Copenhagen | Bratislava | Bratislava | Stockholm | Budapest | Stockholm | Ljubljana | Ljubljana |
| Lisbon | Ljubljana | Ljubljana | Lisbon | Bratislava | Bratislava | Stockholm | Helsinki |
| Ljubljana | Helsinki | Helsinki | Helsinki | Ljubljana | Helsinki | Bratislava | Stockholm |
| Vilnius | Riga | Riga | Riga | Vilnius | Ljubljana | Helsinki | Roma |
| Riga | Tallinn | Tallinn | Vilnius | Riga | Tallinn | Tallinn | Vilnius |
| Tallinn | Vilnius | Vilnius | Tallinn | Tallinn | Vilnius | Vilnius | Lisbon |

## 6. Conclusions

Previous studies on potential accessibility have shown that self-potentials have an important contribution to the accessibility level of locations. In the most urbanized regions this contribution sometimes outweighs 50% of their overall accessibility level.

The weight of self-potential depends on the method used to determine internal travel distances. In many cases this is done by using distance metrics characterized by a high level of abstraction. We contribute to the accessibility literature by exploring the impacts of choosing different internal distance definitions that vary in terms of complexity. Furthermore we have improved the estimation of internal travel time by using more disaggregated sources of data (Tele Atlas/TomTom) and more detailed methodologies. The approach proposed within this study was compared with more coarse approaches for measuring internal travel times.

The results show that using fixed values of internal travel time gives underestimations for larger regions, while area based approaches, which assume that all trips start or end at a central point within a region, lead to a general underestimation of internal travel distances. Additionally, area based approaches do not consider traffic along transport networks, which also contributes to an underestimation of internal distances. These coarse assumptions are especially problematic in regions that have dispersed population, higher road density and congestion levels. Our results are in line with those of Frost and Spence (1995), confirming that changing the internal distance measure does not only impact on accessibility values but also changes the spatial distribution of accessibility. Thus, our results justified the need for more complex and accurate metrics of internal travel time.

Previous studies have also shown that self-potentials and thus the way internal travel times are measured, become even more important with higher values of distance decay, since activities located nearby, gain a major relevance. Our results confirm this idea and show that high distance decay values change the accessibility levels but also the accessibility distribution.

The present paper also contributes with an internal travel time measure, combining network analysis with ICT data from Tele Atlas/TomTom database. This method could be used to calculate internal travel times more accurately and improve accessibility analyses and transport models (e.g. TRANS-TOOLS).

## Acknowledgements

The views expressed are purely those of the author and may not in any circumstances be regarded as stating an official position of the European Commission.

## References

Anderson, T. R. (1956). Potential models and the spatial distribution of population. *Papers of the Regional Science Association* 2, 175-182. doi:10.1111/j.1435-5597.1956.tb01563.x

Baradaran, S., and Ramjerdi, F. (2001) Performance of Accessibility Measures in Europe *Journal of Transportation and Statistics* 4, 31-48.

Bewley, R., and Fiebig, D. G. (1988) A flexible logistic growth model with applications to telecommunications. *International Journal of Forecasting,* 4, 177-192. doi:10.1016/0169-2070(88)90076-3

Bruinsma, F., and Rietveld, P. (1998). The accessibility of European cities: theoretical framework and comparison of approaches. *Environment and Planning A,* 30, 499-521. doi:10.1068/a300499

Clark, C., Wilson, F., and Bradley, J. (1969). Industrial location and economic potential in Western Europe. *Regional Studies,* 3, 197-212. doi:10.1080/09595236900185201

Condeço-Melhorado, A., Gutiérrez, J., and García-Palomares, J. C. (2011). Spatial impacts of road pricing: Accessibility, regional spillovers and territorial cohesion. *Transportation Research A,* 45, 185-203. doi:10.1016/j.tra.2010.12.003

Condeço-Melhorado, A., Gutiérrez, J., and García-Palomares, J. C. (2013). Influence of distance decay on the measurement of spillover effects of transport infrastructure: a sensitivity analysis. *Geofocus,* 13, 22-47.

Dijkstra, E. W. (1959). A note on two problems in connexion with graphs. *Numerische Mathematik,* 1, 269–271. doi:10.1007/bf01386390

Dundon-Smith, D., and Gibb, R. A. (1994). The Channel Tunnel and the regional economic development. *Journal of transport Geography,* 2, 178-189. doi:10.1016/0966-6923(94)90003-5

Fotheringham, A. S., and O'Kelly, M. E. (1989). *Spatial Interaction Models: Formulations and Applications*. Dordrecht: Kluwer Academic Publishers.

Frost, M. E., and Spence, N. A. (1995C). The rediscovery of accessibility and economic potential: the critical issue of self-potential. *Environment and Planning A,* 27, 1833-1848. doi:10.1068/a271833

Gutiérrez, J. (2001). Location, economic potential and daily accessibility: an analysis of accessibility impact of the high-speed line Madrid-Barcelona-French border. *Journal of Transport Geography,* 9, 229-242. doi:10.1016/s0966-6923(01)00017-5

Gutiérrez, J., Condeço-Melhorado, A., and Martín, J. C. (2010). Using accessibility indicators and GIS to assess spatial spillovers of transport infrastructure investment. *Journal of Transport Geography,* 18, 141-152. doi:10.1016/j.jtrangeo.2008.12.003

Handy, S. (1993). Regional Versus Local Accessibility: Implications for Non-work Travel. *Transportation Research Record,* 1400, 58-66.

Hansen, W. G. (1959). How accessibility shapes land-use. *Journal of American Institute of Planners,* 25, 73-76. doi:10.1080/01944365908978307

Harris, C. D. (1954). The market as a factor in the localization of industry in the United States. *Annals of the Association of American Geographers,* 44, 315-348. doi:10.1080/00045605409352140

Haynes, R., Lovett, A., and Sünnenberg, G. (2003). Potential accessibility, travel time, and consumer choice: geographical variations in general medical practice registrations in Eastern England. *Environment and Planning A,* 35, 1733-1750. doi:10.1068/a35165

Head, K., and Mayer, T. (2004). Market Potential and the Location of Japanese Investment in the European Union. *Review of Economics and Statistics,* 86, 959-972. doi:10.1162/0034653043125257

Holl, A. (2007). Twenty years of accessibility improvements. The case of the Spanish motorway building programme. *Journal of Transport Geography,* 15, 286-297. doi:10.1016/j.jtrangeo.2006.09.003

Houston, C. (1969). Market potential and potential transportation costs: an evaluation of the concepts and their surface on the USSR. *Canadian Geographer,* 13, 216-236. doi:10.1111/j.1541-0064.1969.tb00958.x

Huang, T., Yang, G., and Tang, G. (1979). A fast two-dimensional median filtering algorithm. *IEEE Trans. Acoust., Speech, Signal Processing*, 27, 1-18. doi:10.1109/tassp.1979.1163188

Ingram, D. R. (1971). The concept of accessibility: the search of an operational form. *Regional Studies,* 5, 101-107. doi:10.1080/09595237100185131

Kotavaara, O., Antikainen, H., and Rusanen, J. (2011). Population change and accessibility by road and rail networks: GIS and statistical approach to Finland 1970–2007. *Journal of Transport Geography,* 19, 926-935. doi:10.1016/j.jtrangeo.2010.10.013

Levinson, D. M. (1998). Accessibility and the journey to work. *Journal of Transport Geography,* 6, 11-21. doi:10.1016/s0966-6923(97)00036-7

Linneker, B., and Spence, N. (1996). Road transport infrastructure and regional economic development: The regional development effects of the M25 London orbital motorway. *Journal of Transport Geography,* 4, 77-92. doi:10.1016/0966-6923(96)00001-4

Martínez, L. M., and Viegas, J. M. (2013). A new approach to modelling distance-decay functions for accessibility assessment in transport studies. *Journal of Transport Geography,* 26, 87-96. doi:10.1016/j.jtrangeo.2012.08.018

Östh, J., Reggiani, A. & and Galiazzo, G. (2014) Conventional and New Approaches for the Estimation of Distance Decay in Potential Accessibility Models: Comparative analyses. 15-37. In Condeço-Melhorado A., Reggiani A. and Gutiérrez J. (ed*) Accessibility and spatial interaction*, Edward Elgar (EE). doi:10.4337/9781782540731.00008

Ottaviano, G. I. P., and Pinelli, D. (2006). Market potential and productivity: Evidence from Finnish regions. *Regional Science and Urban Economics,* 36, 636-657. doi:10.1016/j.regsciurbeco.2006.06.005

Owens, D.,W., and Coombes, M. G. (1983). *An index of peripherality for local areas in United Kingdom.* Economics and Statistics Unit, Scottish Economic Planning Department, Report Number, RP6.

Paez, A. (2004). Network Accessibility and the Spatial Distribution of Economic Activity in Eastern Asia. *Urban Studies,* 41, 2211-2230. doi:10.1080/0042098042000268429

Paez, A., Mercado, R., Farber, S., Morency, C., and Roorda, M. (2010). Accessibility to health care facilities in Montreal Island: an application of relative accessibility indicators from the perspective of senior and non-senior residents. *International Journal of Health Geographics,* 9, 52. doi:10.1186/1476-072X-9-52

Portnov, B. A., Axhausen, K. W., Tschopp, M., and Schwartz, M. (2011). Diminishing effects of location? Some evidence from Swiss municipalities, 1950–2000. *Journal of Transport Geography,* 19, 1368-1378. doi:10.1016/j.jtrangeo.2011.07.017

Reggiani, A., Bucci, P., and Russo, G. (2011a). Accessibility and Network Structures in the German Commuting. *Networks and spatial economics*, 11 (4), 621-641. doi:10.1007/s11067-010-9149-0

Reggiani, A., Bucci, P., and Russo, G. (2011b). Accessibility and impedance forms: empirical applications to the German commuting networks. *International Regional Science Review,* 34 (2), pp. 230-252. doi:10.1177/0160017610387296

Rich, D. (1980). *Potential models in Human Geography.* Norwich, Report Number, 26.

Rich, D. (1978). Population potential, potential transportation cost and industrial location. *Area,* 10, 222-226.

Salze, P., Banos, A., Oppert, J., Charreire, H., Casey, R., Simon, C., Chaix, B., Badariotti, D., and Weber, C. (2011). Estimating spatial accessibility to facilities on the regional scale: an extended commuting-based interaction potential model. *International Journal of Health Geographics,* 10, 2. doi:10.1186/1476-072X-10-2

Sen, A. (1986). Maximum-Likelihood-Estimation of Gravity Model Parameters. *Journal of Regional Science,* 26 (3), 461-474. doi:10.1111/j.1467-9787.1986.tb01054.x.

Simma, A., and Axhausen, K. W. (2003). Interactions between Travel Behaviour, Accessibility and Personal Characteristics: The Case of Upper Austria. *European Journal of Transport and Infrastructure Research,* 3, 179-197.

Stewart, J. Q. (1947). Empirical mathematical rules concerning the distribution and equilibrium of population. *Geographical Review,* XXXVII, 461-482. doi:10.2307/211132

van Wee, B., Chorus, C., and Geurs, K. T. (2012). ICT and accessibility: research synthesis and future perspectives. 37-53. In Geurs, K. T., Krizek, K., and Reggiani, A. (ed) *Accessibility Analysis and Transport Planning: Challenges for Europe and North America,* Edward Elgar Publishing. doi:10.4337/9781781000113.00009

van Wee, B., Hagoort, M., and Annema, J. A. (2001). Accessibility measures with competition. *Journal of Transport Geography,* 9, 199-208. doi:10.1016/S0966-6923(01)00010-2

Vickerman, R. W., Spiekermann, K., and Wegener, M. (1999). Accessibility and economic development in Europe. *Regional Studies,* 33, 1-15. doi:10.1080/00343409950118878

Wilson, A. G. (1967). A Statistical Theory of Spatial Distributions. *Transportation Research,* 1, 253-269. doi:10.1016/0041-1647(67)90035-4.

Wilson, A. G. (1970). *Entropy in Urban and Regional Modelling*. London: Pion. doi:10.4324/9780203142608

Wilson, A. G. (1971). A family of spatial interaction models, and associated developments. *Environment and Planning,* 3, 1-32. doi:10.1068/a030001.

# Appendix A

## Table A1. Area and population of NUTS-3 regions

| Name | Area (Km2) | Population (2005) |
|---|---|---|
| Vienna | 415 | 1638900 |
| Brussels | 162 | 1013300 |
| Prague | 496 | 1175500 |
| Berlin | 891 | 3386700 |
| Copenhagen | 182 | 595900 |
| Tallinn | 4338 | 521200 |
| Madrid | 8028 | 5918400 |
| Helsinki | 6730 | 1356100 |
| Paris | 106 | 2215200 |
| Athens | 3813 | 3987600 |
| Budapest | 525 | 1697700 |
| Dublin | 925 | 1167600 |
| Roma | 5352 | 3821300 |
| Vilnius | 9733 | 848400 |
| Luxembourg | 2596 | 457300 |
| Riga | 303 | 729700 |
| Amsterdam | 897 | 1208100 |
| Warsaw | 517 | 1697100 |
| Lisbon | 1350 | 2008300 |
| Stockholm | 7112 | 1858500 |
| Ljubljana | 2555 | 493100 |
| Bratislava | 2045 | 602400 |
| London | 109 | 1097100 |

## Table A2. Potential accessibility values of NUTS-3 regions

| Name | Potential accessibility β=1 | | | | Potential accessibility β=2.5 | | | |
|---|---|---|---|---|---|---|---|---|
| | A | B | C | D | A | B | C | D |
| Vienna | 6664 | 13944 | 12457 | 4317 | 43 | 606 | 421 | 5.6 |
| Brussels | 7278 | 19803 | 12611 | 9764 | 39 | 1752 | 384 | 152.5 |
| Prague | 5002 | 8291 | 7300 | 4137 | 22 | 248 | 147 | 7.1 |
| Berlin | 7613 | 12541 | 8681 | 4446 | 56 | 307 | 89 | 5.5 |
| Copenhagen | 4321 | 11419 | 8647 | 3718 | 24 | 937 | 381 | 11.1 |
| Tallinn | 1958 | 1905 | 2039 | 1769 | 5 | 4 | 7 | 2.2 |
| Madrid | 10851 | 7648 | 9064 | 5004 | 105 | 37 | 62 | 9.6 |
| Helsinki | 4586 | 3616 | 4104 | 2127 | 39 | 17 | 27 | 1.9 |
| Paris | 12095 | 56389 | 36388 | 12867 | 104 | 8247 | 2561 | 128.5 |
| Athens | 6500 | 6273 | 6868 | 2781 | 60 | 53 | 70 | 3.2 |
| Budapest | 4543 | 7521 | 7305 | 3331 | 21 | 219 | 195 | 2.8 |
| Dublin | 5015 | 8151 | 6738 | 2791 | 37 | 194 | 105 | 2.6 |
| Roma | 7669 | 6534 | 6379 | 2830 | 66 | 39 | 36 | 1.2 |
| Vilnius | 2090 | 1871 | 1977 | 1792 | 6 | 2 | 3 | 1.2 |
| Luxembourg | 5644 | 6062 | 6298 | 4597 | 23 | 33 | 42 | 5.5 |
| Riga | 1993 | 3154 | 2688 | 2028 | 5 | 114 | 49 | 7.2 |
| Amsterdam | 6887 | 10432 | 9981 | 4870 | 40 | 215 | 184 | 6.5 |
| Warsaw | 4440 | 8308 | 6144 | 3384 | 27 | 292 | 101 | 7.1 |
| Lisbon | 4270 | 5948 | 5405 | 2135 | 31 | 101 | 73 | 1.1 |
| Stockholm | 6666 | 5113 | 5457 | 2630 | 58 | 24 | 30 | 1.6 |
| Ljubljana | 3521 | 3682 | 4104 | 3075 | 8 | 11 | 31 | 2.0 |
| Bratislava | 4339 | 4764 | 4929 | 3472 | 12 | 22 | 29 | 2.0 |
| London | 10669 | 48944 | 30013 | 11424 | 92 | 6983 | 1885 | 115.4 |

## Table A3. Self-potential values of NUTS-3 regions

| Name | Self-potential β=1 | | | | Self-potentials β=2.5 | | | |
|---|---|---|---|---|---|---|---|---|
| | A | B | C | D | A | B | C | D |
| Vienna | 3775 | 10951 | 9470 | 1624 | 42.2 | 604.9 | 420.6 | 5.1 |
| Brussels | 3383 | 15686 | 8536 | 5893 | 37.8 | 1750.7 | 382.4 | 151.5 |
| Prague | 1932 | 5123 | 4148 | 1206 | 21.6 | 247.4 | 146.0 | 6.7 |
| Berlin | 4976 | 9848 | 6009 | 1934 | 55.6 | 306.5 | 89.2 | 5.2 |
| Copenhagen | 2088 | 9145 | 6380 | 1546 | 23.3 | 937.0 | 380.9 | 11.0 |
| Tallinn | 428 | 384 | 505 | 306 | 4.8 | 3.6 | 7.2 | 2.1 |
| Madrid | 9404 | 6201 | 7614 | 3602 | 105.1 | 37.1 | 62.0 | 9.5 |
| Helsinki | 3459 | 2491 | 2976 | 1037 | 38.7 | 17.0 | 26.6 | 1.9 |
| Paris | 9302 | 53491 | 33505 | 10109 | 104.0 | 8246.8 | 2560.7 | 128.0 |
| Athens | 5332 | 5102 | 5696 | 1645 | 59.6 | 53.4 | 70.3 | 3.2 |
| Budapest | 1831 | 4719 | 4508 | 788 | 20.5 | 218.4 | 194.7 | 2.5 |
| Dublin | 3300 | 6410 | 5003 | 1129 | 36.9 | 194.0 | 104.4 | 2.5 |
| Roma | 5922 | 4782 | 4629 | 1181 | 66.2 | 38.8 | 35.8 | 1.2 |
| Vilnius | 531 | 318 | 417 | 270 | 5.9 | 1.6 | 3.2 | 1.1 |
| Luxembourg | 1995 | 2314 | 2553 | 1084 | 22.3 | 32.3 | 41.3 | 4.9 |
| Riga | 480 | 1627 | 1162 | 538 | 5.4 | 113.6 | 49.0 | 7.1 |
| Amsterdam | 3513 | 6930 | 6498 | 1640 | 39.3 | 214.7 | 182.7 | 5.8 |
| Warsaw | 2400 | 6236 | 4081 | 1400 | 26.8 | 292.0 | 101.1 | 7.0 |
| Lisbon | 2749 | 4422 | 3877 | 694 | 30.7 | 100.8 | 72.6 | 1.0 |
| Stockholm | 5190 | 3636 | 3979 | 1217 | 58.0 | 23.8 | 29.9 | 1.5 |
| Ljubljana | 652 | 762 | 1159 | 349 | 7.3 | 10.8 | 30.7 | 1.5 |
| Bratislava | 915 | 1195 | 1353 | 389 | 10.2 | 20.0 | 27.2 | 1.2 |
| London | 8197 | 46390 | 27472 | 8978 | 91.6 | 6982.9 | 1884.5 | 115.1 |