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Indicators of urban form and sustainable urban transport

Introducing simulation-based indicators for the LUISA modelling platform

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Abstract

Sustainable urban transport is a key objective of European Commission policies and often an integral part of debates on efficient and inefficient urban form. Because of the expected relation between sustainable transport and urban form, indicators that communicate potential impacts of sustainable transport policies have repeatedly been requested for the LUISA modelling platform. This report presents three novel indicators that may shed some light on potential transport sustainability impacts of current and future urbanization patterns. These indicators are:

1) A proxy of demand for transport-related energy consumption, which is a measure that indicates for every inhabited 1 km grid cell in Europe the average Euclidean distance travelled for social visits, given a number of assumptions and methodological limitations;
2) Road-link specific transport consumption, which is a measure that indicates how many vehicle kilometres are travelled in any road-carrying grid cell in Europe; and
3) A measure of urban form efficiency by ease of access to potential public transport services, which is a measure that indicates to what degree the population distribution in a city is supportive for an effective public transport system.

Because of methodological limitations and data availability the indicators are based on simulation exercises that take into account only fine resolution population distributions and in some cases also transport supply. Thus these indicators can give insight into the degree in which management of urban growth may encourage sustainable transport. The report presents the indicators at hand and some first results in which the emphasis is put on differences between European cities. The report's conclusions reflect on the usefulness of the indicators for policy evaluations, and on research that might be conducted in the future.

1. Introduction

Sustainable urban transport, characterised by reducing energy consumption, CO2 and noxious gas emissions, is a key objective of the European Commission (EC). Various strategies have already been identified to reduce the energy dependence of transportation; Gilbert and Dajani (1) broadly categorized those strategies into: I) inducing shifts to more efficient modes, II) increasing the efficiency of current modes, and III) decreasing travel demand. Because of its expected impact on travel demand, urban form is often noted to affect transport energy consumption and the potential for sustainable transport. Therefore there is a need at the EC for the indicators that show the relation between urban form, transport consumption and transport efficiency; for the current status-quo of European cities as well as for their potential future forms. The LUISA ('Land Use-based Integrated Sustainability Assessment') modelling platform is specifically set up to provide assessments of the current and future state of territorial sustainability in an integral manner. For more information on LUISA we refer to (2–4). Transport sustainability and in particular the relation between urban form and sustainable transport are often demanded as outputs of LUISA.

This report will introduce three novel indicators of the LUISA modelling platform that deal with sustainable transport, energy consumption and urban form. These indicators have been used to inform the upcoming 2016 reports on cities (5) and on energy consumption downscaling (6). Commonly, compact urban development is considered favourable for sustainability. Besides other advantages of compact urban development (7), there is growing evidence that compact cities favourably affect the mode choice for walking, cycling and public transport (8) and that in fact such cities produce less car vehicle kilometres travelled (9,10). However, many aspects of transport energy consumption and travel demand are under debate in the academic literature. Most importantly, there is no consensus that urban densities unequivocally affect transport energy consumption or trip frequency (11,12). In fact, transport energy consumption might be related much more to fuel prices and family income (13). Other issues raised in the debate on the sustainability of compact urban development are related to endogeneity and induced demand (14); the degree in which people commute shorter distances in more compact cities (15,16); the trade-off between energy-efficient transport technology and energy-efficient urban form (10,17); and the balance between compactness and overconcentration (18). Tackling the many reciprocities between urban form, travel demand, fuel prices, car ownership, mode choice and socio-economic status for the whole EU territory would go beyond the current capacity of the LUISA modelling platform and would require a substantial investment in data in the short-term.

In order to satisfy urgent needs for policy analysis, three indicators have been developed in the LUISA modelling platform, which can be used to approximate the relation between urban form, road networks, travel demand and modal shift. These indicators describe city-specific potential for sustainable transport, estimate the geography of transport energy consumed on Europe's road and measure urban form efficiencies based on potential public transport service developments. Those use existing urban patterns, road networks and population distributions as input data, but furthermore are based on a number of assumptions concerning travel behaviour, transport management, and the existence of a relationship between distances travelled, mode choice and energy efficiency.

In section 2, a proxy of travel demand for each inhabited 1 x 1 km grid cell in Europe is introduced, along with the first findings from that method. This indicator can be used to understand the potential transport energy efficiency of cities, regions and countries; and it can be used to evaluate the impacts of future changes in land-use patterns and transport networks on sustainable transport potential. This section furthermore introduces an exercise in which the usage of roads is modelled using a transport model between 5 x 5 km grid cells and the same assumptions used in section 2. Preliminary results are provided in that section as well. This exercise is instrumental for downscaling national energy consumption figures to local levels (6), and it can additionally be used to indicate changes in pressure on Europe's existing road network. Section 3 introduces an indicator in which fine-resolution population grids are used to measure to what degree cities can support an effective public transport system; the results indicated for this analysis are based on the recently published EUROSTAT 2011 population grid data (19). Finally, section 4 offers some general conclusions arising from the presented indicators.

2. A proxy of demand for transport-related energy consumption

There is a considerable debate on the degree in which energy consumption for transport depends on the shape and level of compactness of urban settlements (8,12,13,17). This is relevant for the expansion of residential areas as well as for working, shopping and recreation space. Given that the LUISA modelling platform currently only simulates inhabitants explicitly, we focus on the transport energy efficiency of residential areas here. Aspects that are relevant to understand energy use for transport for the inhabitants of a particular area include the following:

1) Available opportunities;
2) Choice of destination;
3) Choice of transport mode;
4) Fuel consumption of the used transport mode;
5) Socio-economic status.

However, it is difficult to get an accurate estimate of the amount of energy needed for transportation. There are several reasons for this complexity. First of all, there are reciprocities between travel distance and trip frequency: e.g., one that lives farther away from a shop presumably goes to the shop less frequently. This may yield unexpected results: driving eight kilometres once by car presumably yields better fuel efficiency compared to driving one kilometre eight times, because cars are in general more fuel efficient on longer distances. Furthermore, there are also reciprocities between mode availability, mode choice, mode preferences, residence choice and destination choice: e.g., one that can only move by foot will choose central housing or is restricted to destinations in the immediate vicinity; one that has many transport modes available may still choose to pick destinations that are reachable by bicycle. Lastly, estimating the fuel consumption of motorized vehicles on a trip is not straightforward, e.g., a one-passenger trip with a hybrid car is presumably more fuel efficient than a bus. All in all, any practically achievable estimate of true fuel consumption will have to be nuanced in many ways, and will presumably face repeated challenges of its validity.

To steer away from these threats and still have a straightforward indicator of the level of energy efficiency of residential areas, we propose a simple proxy indicator in which, for every inhabited 1 x 1 km grid cell in selected urban regions, the average Euclidean travel distance is computed. The key question answered by this indicator is: *if every inhabitant makes the same amount of trips to destinations only within 30 minutes, what Euclidean distance would the inhabitants travel on average*? The underlying assumption is that longer travelled Euclidean distances are associated with higher energy consumption and reduced opportunities for energy efficient transport modes such as walking and cycling. The limitation that every inhabitant makes only one trip removes the troublesome reciprocities between distance, trip frequency, urban form, car ownership, fuel prices and socio-economic status. For calculations only trips to destinations within 30 minutes of travel time are concerned. This has a practical reason: to compute this indicator, a matrix with travel-times from all grid cells to all other grid cells has to be obtained, and this can only be achieved if the number of destinations is held reasonably low. Restricting travel times has computational advantages in software such as GeoDMS (20), where shortest path algorithms have n-complexity, with n being the number of origins, and the memory and computation burden depends completely on the threshold distances that can be applied to the shortest path algorithm. Regardless of practical considerations, we expect that a threshold of 30 minutes already provides a feasible limit which can be associated with short-distance trips such as commuting, shopping and social visits. In fact, a recent JRC survey shows that working day trips in most surveyed European countries are shorter than 30 minutes (21), and we therefore expect that this restriction does not severely affect the validity of the findings.

2.1 Indicator definition

The transport-related energy consumption indicator is computed as in (1):

$$D_i = \frac{1}{n}\sum_{j=1}^{n} d_{ij}T_{ij}, \qquad (1)$$

so that averaged Euclidean distances D for origin grid cells *i* are obtained from a matrix of Euclidean distances *d* to destinations *j* given estimated number of trips *T*. Those trips are again computed using an origin-constrained spatial interaction model (22). For the sake of elegance, we obtain this model as a special case from Alonso's general theory of movements (23) as in (2):

$$T_{ij} = A_i^{(1-\gamma)} P_i (P_j - I_{ij}) f(c_{ij}), \qquad (2)$$

in which the number of trips depends on number people P at the origin and the destination. The population numbers at the destination are reduced with 1 in the case that the destination and the origin are identical. This is done using values of I (3):

$$I_{ij} = \begin{cases} 1 \; if \; i = j \\ 0 \; if \; i \neq j \end{cases}, \qquad (3)$$

which takes the value of 1 if the destination and the origin are the same. The reduction of people (and thus trip attractiveness) at the destination is done to impose the rule that *people cannot visit themselves.* This is relevant in particular in sparsely populated grid cells, where the inclusion of self-visits may have a significant effect on the grid cell's trip distributions.

The definition of T also depends on the distance-decayed generalised travel costs *c.* In the prototype that is being demonstrated here, the distance decay function is set as ${c_{ij}}^{-1.5}$; the generalised travel costs are obtained as shortest-path travel times using the car.

First tests of the method used data generated and presented by Stępniak and Rosik (24) and applied here with explicit permission. The later European-wide implementation uses the fully available European coverage of roads provided by commercial road-data provider TeleAtlas. By using car travel times to obtain destination choices, this model imposes that inhabitants decide on their destinations based on car availability. If detailed travel time matrices for other transport modes (walking, cycling, and public transport) may be obtained, the used car-dependent travel times can be replaced by travel times from the fastest available transport mode per origin-to-destination relationship.

Lastly the number of trips depends on the accessibility factor A (4):

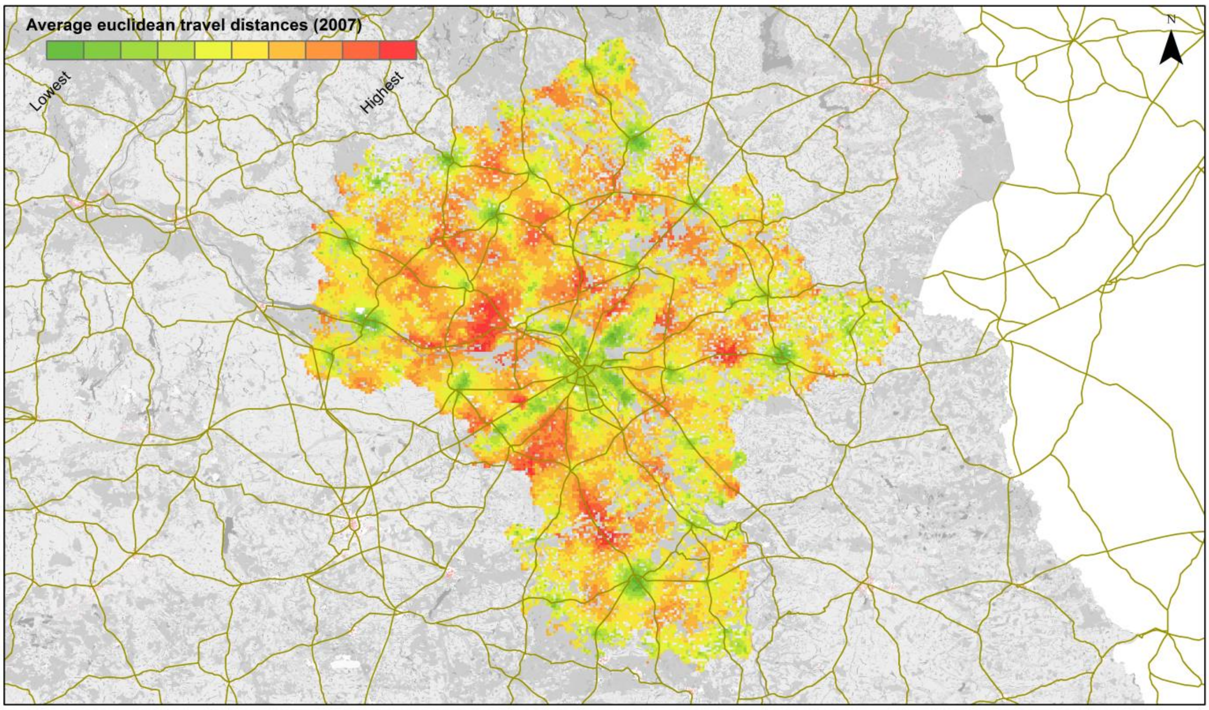
$$A_i = \left\{ \sum_j (P_j - I_{ij}) f(c_{ij}) \right\}^{-1}, \tag{4}$$

which can in this case be interpreted as accessibility to people. It is, in Alonso's theory of movement (23), used as a balancing factor that ensures that the production of trips at an origin does not increase proportionally with changes in transport costs. This is done by keeping the parameter γ between 0 and 1; see equation (2). In this case, γ has been kept at 1 to ensure that the production of trips from an origin equals the number of inhabitants at the origin, but may be changed to take into account that the number of trips again depends on value of travel costs or in fact the local level of A.

2.2 Results

2.2.1. Average travel distances: Masovia Region in Poland

A prototype run for the Masovia region in Poland that contains Warsaw has been computed as an example of regional differences in modelled travel distances. If the average Euclidean travel distances are plotted for the whole region it is immediately clear that city centres are, as can be expected, associated with the shortest average distances (see Figure 1). In particular peripheral areas with low population densities stand out as areas with higher average Euclidean distances. The lack of attractive destinations in the vicinity, amplified by the detraction of 1 in the attractiveness of intrazonal trips causes substantial increases in average travel distance. Not presented here are additional statistics on the computed indicator that consider the breakdown of trips per origin. Such statistics could for example indicate the number of trips within 1000 meters (where walking is a vital substitute for the car) or within 3000 meter (where cycling is a vital substitute).



Average Euclidean distances given an origin-constrained spatial interaction model and over the road travel times.
Study area: Warsaw and surroundings, Poland. Population at the origins differs as a result of different LUISA scenario assumptions.
Map by Chris Jacobs-Crisioni, Unit H08, JRC

Travel times used for this study from Instytut Geografii i Przestrzennego Zagospodarowania PAN, Warsaw, Poland

Figure 1: Average Euclidean travel distances in the Masovia region, Poland.

The introduced indicator might be used to explore the potential for sustainable transport in alternative urban growth scenarios. As an example, the case of Warsaw from Poland is examined in detail. This is done using the previously computed travel time matrices (24) and the population distribution outcomes of the Compact Development and Business-As-Usual (BAU) scenarios that have previously been run in LUISA for a previous project (4). In the BAU scenario, the current urbanization process is assumed to continue without inhibition; in the Compact scenario, urbanization is only allowed in the immediate vicinity of existing urban areas. These different scenarios were created specifically to understand the impact of local spatial policies on urban expansion patterns and associated sustainability impacts. In this context they provide a useful example to show the effects of different urban development cases on the developed indicator.

The modelled average travel distances according to the two LUISA scenarios taken into account are shown in Figure 2. Although the central areas with low average travel distances are visually dominant in both scenarios, in the BAU scenario (right-side of the figure) there is slightly more urban development in Warsaw's periphery as well as more fully isolated urban development patches far from the city. Although the visible impacts of the two scenarios are limited, the more abundant scattered urban development in the BAU scenario causes considerably higher average travel distances. Thus, in the Compact scenario (left-side of the figure) an inhabitant of the Warsaw region travels 10.1 kilometres on average, while in the BAU scenario the region's inhabitants would travel 500 metres more on average. It is highly conceivable that a 500 meter increase in travel distance will sway many of the trips in the city from slow transport modes to car-based trips. Thus, the implications of urban development for the potential for sustainable transport may be substantial.

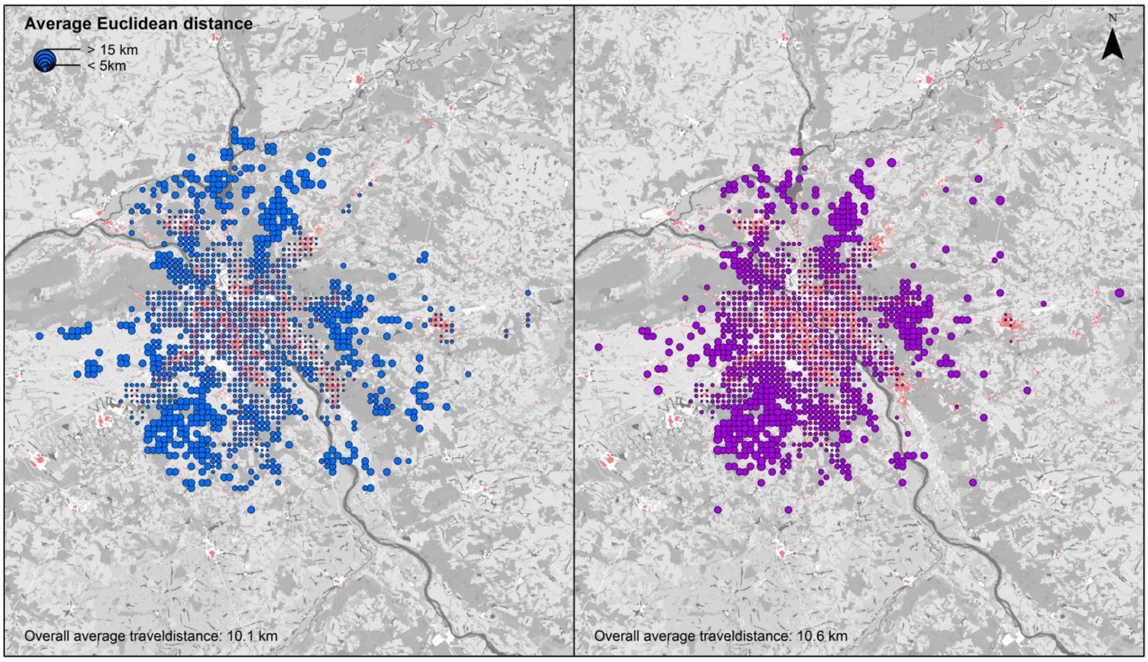


Figure 2: An application of the average Euclidean travel distances indicator in Warsaw, Poland: Compact vs BAU future urban development.

2.2.1 Average travel distances: A Europe-wide grid map

To obtain Europe-wide average travel distances, the method has been applied using the EUROSTAT 2011 population grid data (19). Unfortunately, due to network data unavailability, results are not available for the islands of Denmark, Greece and Spain, as well as for the most Northeastern region of Poland. For the sake of computational simplicity, the analysis has been done separately with subsets of origins and destinations in large regions. Thus, for each large region (a slightly adapted version of the NUTS1 regional division to be precise), average travel distances are computed between the origins and destinations within that region. This causes some bias in border pixels where travel distances may be under or overestimated; our estimation is that this bias is fairly limited due to the fact that NUTS1 regions generally have typical centre-periphery patters in which border pixels are mostly oriented on the region's centre. In this exercise the general patterns of the Masovia region are repeated throughout all Europe; see Figure 3. Noteworthy is the dominance of long travel distances around the major metropolises of North-western Europe such as Brussels, Paris and the Randstad and Ruhr areas. If we take Barcelona and Stockholm as cases, cities that stand out as two cities with very contrasting urban patterns. The common pattern in both of the two cities is that average travelled distance is lower in the city centres and higher in the suburbs and rural areas. However, it becomes immediately clear that the city of Stockholm has a much more scattered urban development pattern with relatively low average travel distances. This is no doubt caused by the different urban structures of those cities. Barcelona has a very dominant city centre in which a large portion of the population is concentrated and most trips are terminated. In contrast, Stockholm has a number of sub-centres that draw a considerable amount of trips locally.

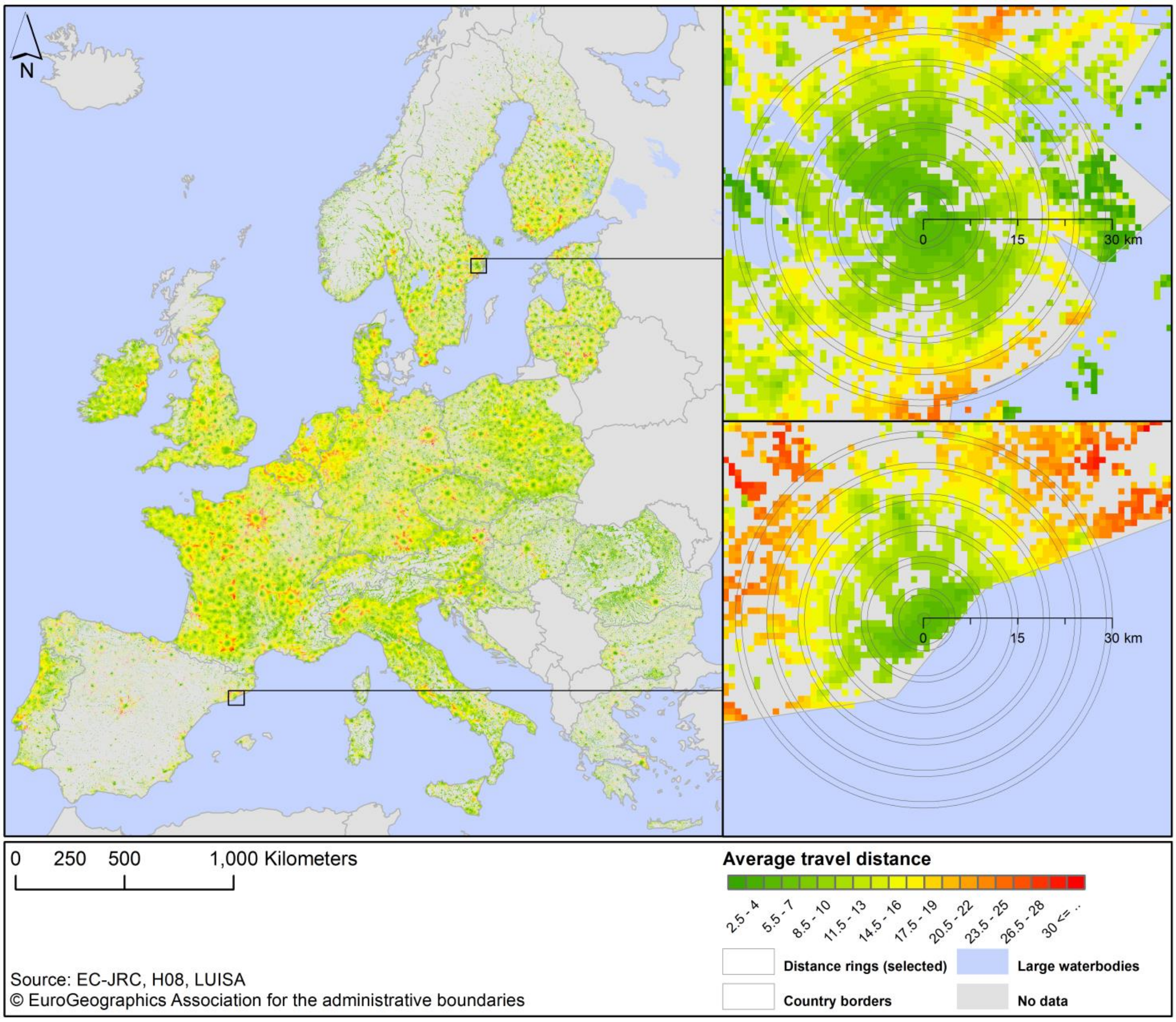


Figure 3: Average travel distances (km) in Europe, with particular focus on Stockholm and Barcelona. EUROSTAT 2011 population grids have been used to describe population distribution.

2.2.2. A comparison of Functional Urban Areas

In order to obtain a comparison of the relative performance of urban areas, travel distances have been averaged for Europe's Functional Urban Areas. The results are shown in Figure 4. In that map the dominance of long travel distances in Europe's Northwestern cities is immediately clear. In contrast, cities in the Mediterranean region and in Europe's newest member states have substantially lower average travel distances. The areas of Madrid and Milan make surprising exceptions, with considerably higher average travel distances.

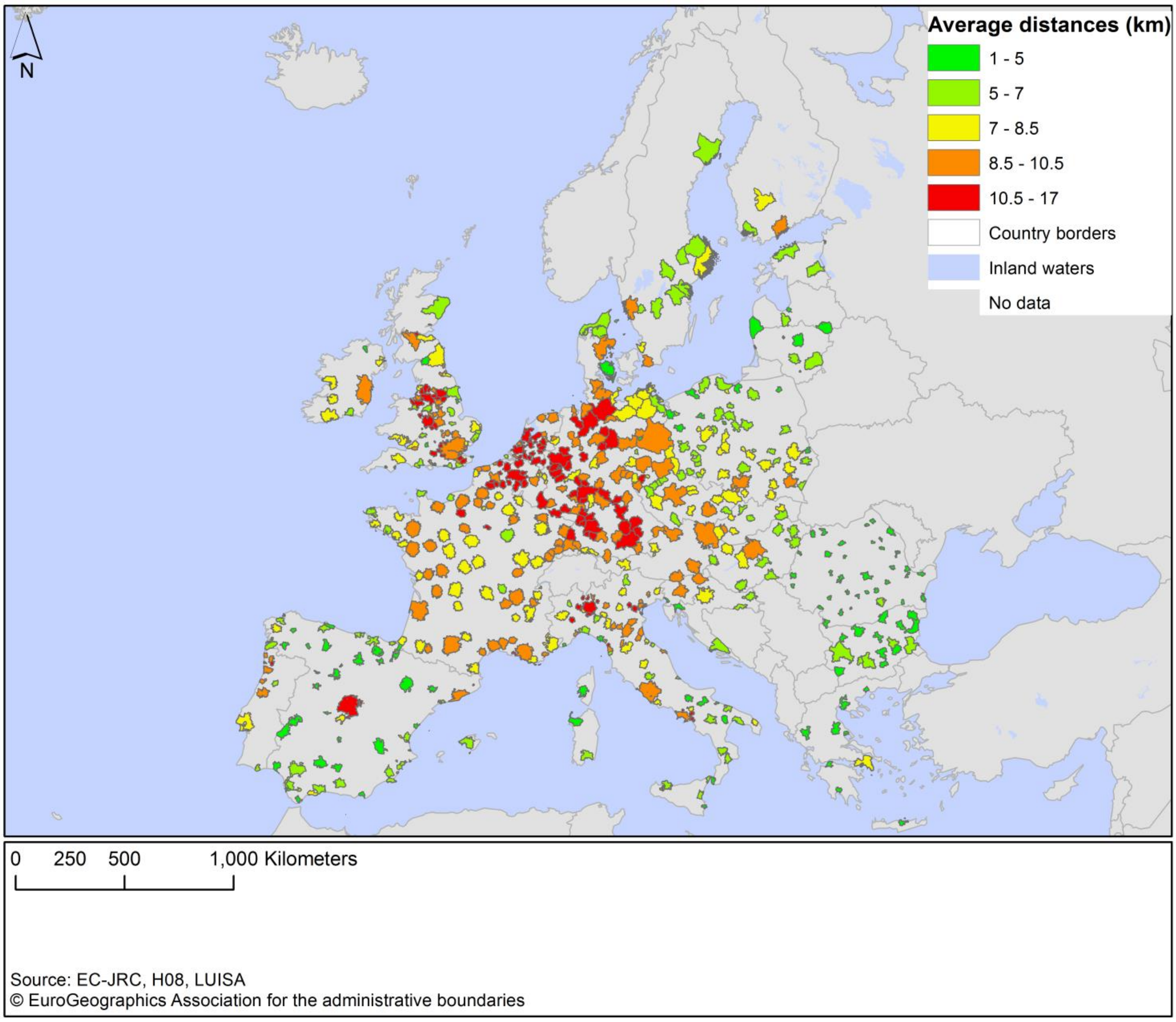


Figure 4: Average travel distances in Europe's functional urban areas.

Table 1 shows the 10 best and 10 worst performing functional urban areas in terms of modelled travel distances according to the indicator at hand. It includes average potential accessibility levels A as computed in (4) and the population-weighted densities of Europe's FUAs. Population-weighted density is a method to compute urban densities in such a way that effects of the shape and size of areal units are less dominant by indicating the average density in which each resident lives (25). For a recent discussion of issues related to areal unit size and shape, commonly identified as aspects of the Modifiable Areal Unit Problem, we refer to Jacobs-Crisioni et al. (26). If the expectations of the advocates of compact urban development hold true, higher population-weighted densities may be expected to profoundly lower average travel distances.

From the table of city performance it becomes immediately clear that urban areas with high population-weighted densities (Zaragoza, Thessaloniki, Bucarest) or cities with very low accessibility values (Bournemouth-Poole, Tallinn) yield very low average travel distances; while urban areas with relatively low population-densities and high accessibility values perform much worse. Browsing the table, it becomes clear that one relevant factor is missing from this table, namely a city's greater spatial context. All of the best performing urban areas are relatively isolated, with no attractive destinations outside of the observed urban area. In contrast, most of the poorly performing urban areas are part of a larger urban network where adjacent urban areas exchange travel flows. This is for example the case for Amsterdam and Utrecht, as well as for the Ruhrgebiet, Düsseldorf, Köln and Bonn urban areas. Clearly, such overlaps in zones of influence and the modelled competition for trips has a substantial impact on modelled average travel distances.

Table 1: Large European functional urban areas ranked by estimated average travel distance, including potential accessibility levels and population-weighted densities.

Rank	Cityname	Country	Average distance	Potential accessibility	Population-weighted density
1	Zaragoza	ES	3.8	25438	197
2	Thessaloniki	GR	4.2	21695	151
3	Riga	LV	4.6	24106	72
4	Granada	ES	5.1	18312	82
5	Bucuresti	RO	5.2	49040	164
6	Bournemouth-Poole	UK	5.4	10434	34
7	Bilbao	ES	5.5	21204	148
8	Palermo	IT	5.6	16691	86
9	Catania	IT	5.6	21289	59
10	Tallinn	EE	5.7	3756	57
	....	...	...	...	...
106	Stuttgart	DE	11.6	24326	34
107	Braunschweig-Salzgitter-Wolfsburg	DE	11.7	10369	23
108	Amsterdam	NL	11.9	32291	59
109	Münster	DE	12.0	15893	31
110	Frankfurt am Main	DE	12.8	25976	39
111	Gent	BE	13.2	21857	27
112	Bonn	DE	13.9	27044	28
113	Köln	DE	13.9	51575	48
114	Utrecht	NL	14.2	41620	50
115	Ruhrgebiet	DE	14.9	50923	38
116	Düsseldorf	DE	15.9	63933	47

Table note: only functional urban areas with at least 500,000 inhabitants are considered. Some cities may be missing because the estimated data is missing.

2.3. Analysis of factors causing travel distance disparities

The last section's results make clear that the often presumed relation between average travelled distances and urban density is not as straightforward as it seems. In fact, modelled average travelled distances are at least the result of a complex interaction between urban densities, accessibility and greater spatial context. To show this interaction, travel distances have been made relative to the average of large urban areas. This indicator of relative distances is defined as $RD_i = D_i / \frac{1}{n} \sum D$ and is computed for the 116 Functional Urban Areas in Europe with at least 500,000 inhabitants. The included urban areas have been categorized into areas with low ($RD_i < 0.8$), medium ($0.8 \leq RD_i \geq 1.2$) and high ($RD_i > 1.2$) average travel distances. Subsequently, the average accessibility levels and population-weighted densities are plotted for those three groups of functional urban areas in Figure 5.

The trend lines of the groups in that graph clearly demonstrate the interaction between densities and accessibility. In all cases, accessibility and densities are proportional; this is logical, as both variables may be expected to rise with increase population numbers. However, in low travel distance cities, minimum population-weighted densities are higher while average accessibility values are lower and increase less with increases in population-weighted densities than in cities with medium travel distances. In contrast, cities with high average travel distances are characterized by generally low population-weighted densities and high accessibility values that increase substantially with higher population-weighted densities.

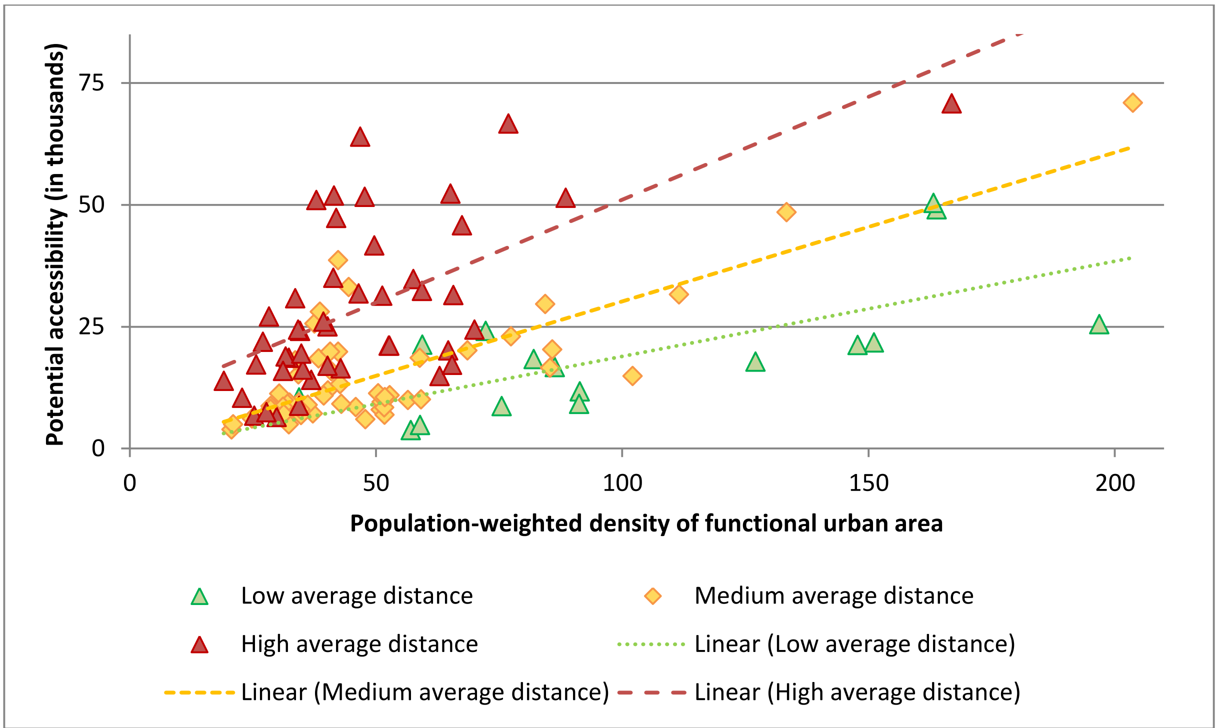


Figure 5: Population weighted densities versus potential accessibility levels in Europe's most populous functional urban areas for different average travel distance classes

This yields the hypothesis that average travel distances in cities are generally subject to two opposing forces: on the one hand, high potential accessibility values where a well-developed transport system offer many attractive destinations within a wide geographical range; and on the other hand, high densities that offer many attractive destinations within a limited distance. To test this hypothesis a regression analysis has been executed of 663 functional urban areas for which data was available. The following equation has been fitted:

$$D_i = \beta 0 + \beta 1 RA_i + \beta 2 RPD_i + \varepsilon, \qquad (5)$$

in which relative potential accessibility $RA_i = A_i / \frac{1}{n} \sum A$ and relative population-weighted densities $RPD_i = PD_i / \frac{1}{n} \sum PD$ have been fitted on average travel distances. RPD is based on population-weighted densities *PD*. A straightforward Ordinary Least Squares regression method has been applied to uncover the factors behind the cross-sectional variety in average travel distances. The results of this regression analysis are in Table 2. The results clearly confirm the interaction between travelled distances, potential accessibility and urban densities: higher levels of potential accessibility increase average travel distances, while higher densities decrease those distances.

Table 2: Results regression analysis of the effects of potential accessibility and population weighted densities on average travel distances (in kilometers of Euclidean distance) in Europe's Functional Urban Areas.

Variable	**Coefficient (t-value)**
Potential accessibility	2.18** (26.41)
Population-weighted density	-2.86** (-26.04)
Constant	8.57** (61.28)
N	663
R2	0.62

* p<0.05, ** p<0.01

2.4. Network implications

The definition of fine resolution transport flows enables a further breakdown of the distribution of trips over the transport network. This has been done in order to support the so-called European Regional Energy Balance and Innovation Landscape (EREBILAND) project undertaken by the JRC (6). That project aims at supporting innovative efficient patterns of regional energy supply and demand in Europe. For this project a suite of modelling tools is being deployed to assess the efficiency of measures on energy production and sectoral final consumption, and related regional development strategies. The EREBILAND approach is based on the granular territorial disaggregation of information, and the development of optimisation scenarios at regional scale based on the concept of dynamic land functions.

2.4.1. A proxy of transport consumption at the network link level

Formerly, emissions of transport in Europe at the fine geographical level have been estimated by a number of straightforward proxies based on road categories and distance to populations. To improve those estimates, a transport model has been developed that is roughly based on the assumptions of the previously introduced proxy for transport energy consumption. In this transport model, origin-destination flows are computed between 5 x 5 km grid cells using equation (2). Subsequently those flows are allocated to the very detailed TeleAtlas network by means of the principle that the entire flow is allocated to the route that yields the shortest travel time, thus assuming that the modelled drivers have perfect knowledge of travel options and have a choice behavior that is purely determined by travel time considerations. This is the most straightforward method of flow allocation in transport modelling; for an overview of methods to model route choice behavior we refer to (27).

The allocated flows are subsequently summed into vehicle kilometers travelled by multiplying the summed flow per link with the length of the link. Subsequently, the start and end points of every link are related to an underlying 100 m raster. Subsequently half the vehicle kilometers travelled for each link are associated with the raster through the start and end point. The final raster indicates summed vehicle kilometers travelled for each point, which is then used as a proxy for transport energy consumption. Because the used road network is sufficiently detailed, this yields a map in which roads are accurately represented as line-like structures.

2.4.2. Results

The results of this exercise are demonstrated in Figure 6, Figure 7 and Figure 8. The produced data demonstrates vehicle (passenger car) kilometers travelled for all of Europe, except for a number of Spanish, Greek, British and Danish islands as well as the region surrounding Bialystok in Poland; for those cases, results are not available because of data availability issues. In total, consumed vehicle kilometers have been allocated to 1,092,767 grid cells (roughly 0.05% of the surface mapped in LUISA). Values range from 1,800 to 457,489 vehicle kilometers travelled. The mean value for grid cells with traffic is 5,698; roughly 93% of those grid cells have a value of 31,500 or lower. All in all, the modelled distribution of vehicle kilometers travelled is considerably skewed, reminiscent of well-known network scaling laws (28).

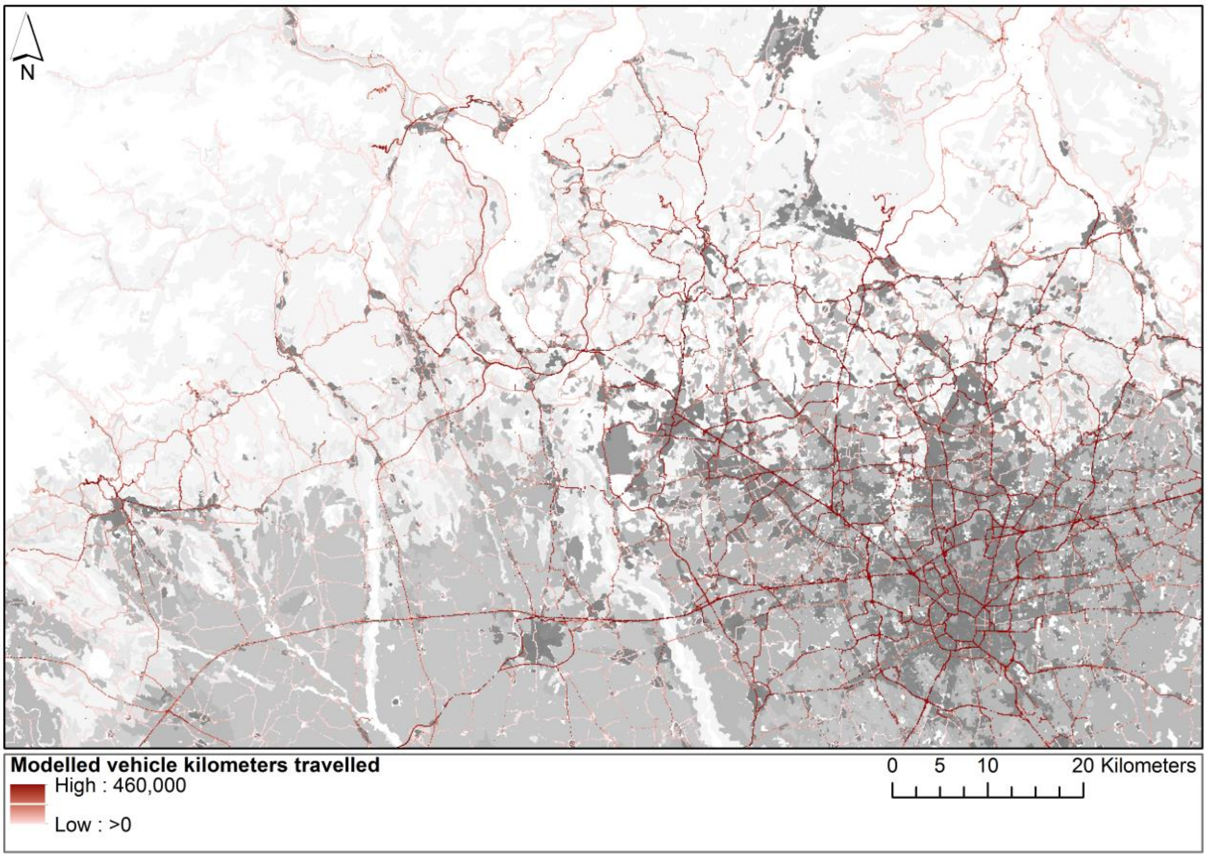


Figure 6: Modelled vehicle kilometers travelled in the region surrounding Milan, Italy.

The modelled vehicle kilometers travelled have been used in the EREBILAND project to disaggregate national-level passenger car data to a fine geographical resolution. However, this method provides ample opportunity for other applications. For example, this method could be used to uncover the impacts of modelled LUISA outputs on road demand; and when linked to existing data on travel time losses due to congestion, this method could be further developed to more closely link LUISA projections with an European-scale transport model such as TRANS-TOOLS (29).

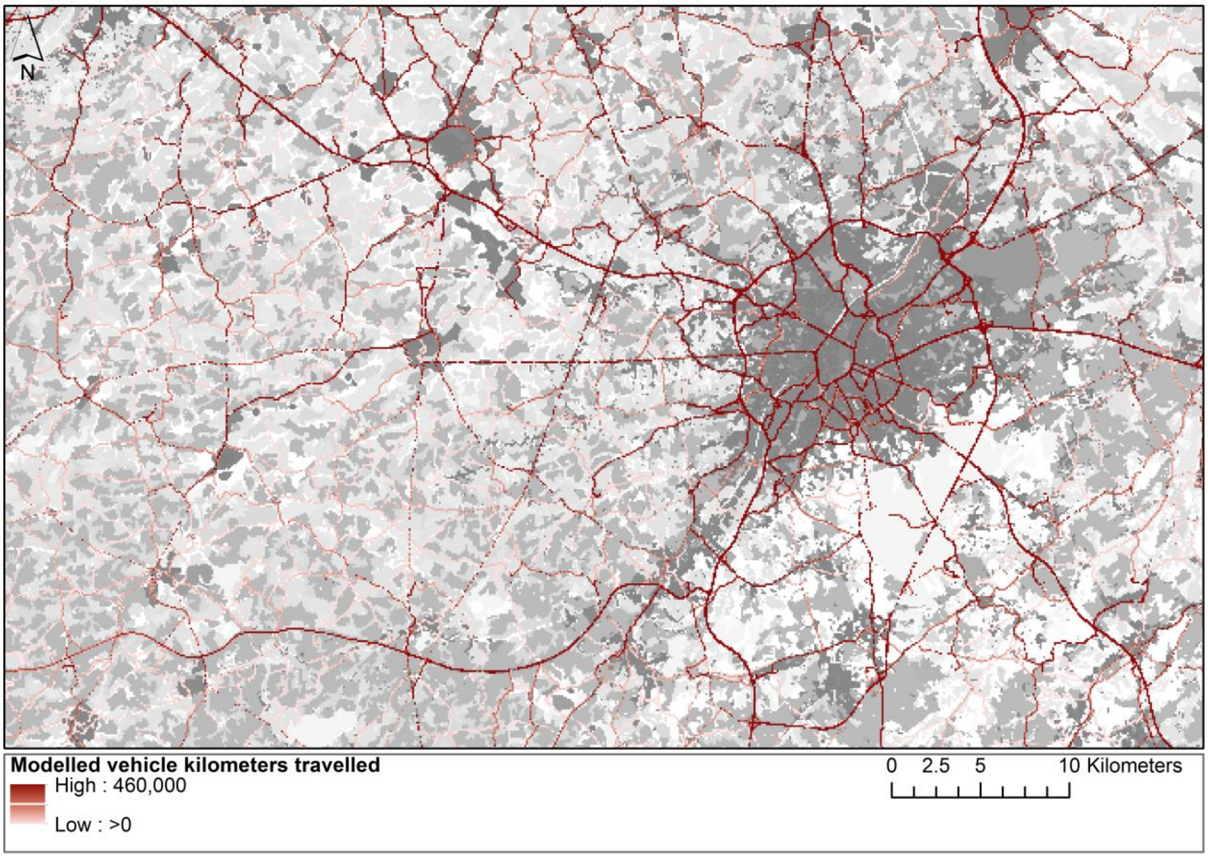


Figure 7: Modelled vehicle kilometers travelled in the region surrounding Brussels, Belgium.

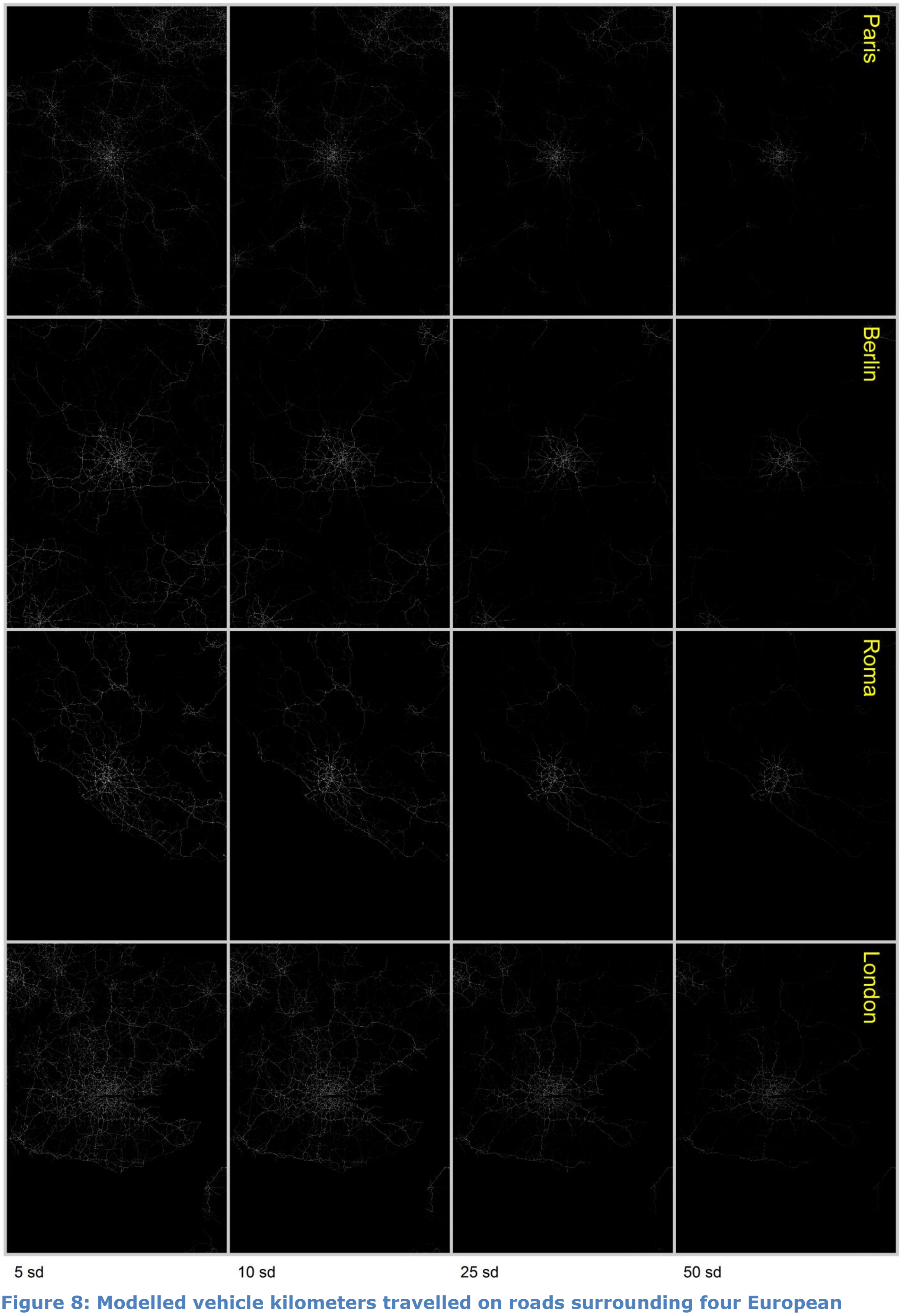


Figure 8: Modelled vehicle kilometers travelled on roads surrounding four European capitals. Lighter values indicate higher values. Different visualization schemes based on standard deviations have been applied to uncover variation in the mapped values.

2.5. Conclusions and further work

This section presents a new indicator that serves as a proxy of energy consumption for transport by computing the Euclidean distance travelled by an urban system's inhabitants given specific limitations. This indicator can be computed for any urban system and is meant to contribute to the sustainability assessment of modelled future city configurations. The presented indicator communicates the average travel distances in case all EU inhabitants would have perfectly identical travel choice behaviours. It thus only captures the effect of spatial context on the potential for sustainable transport, given that everybody's destination choices are exclusively determined by the travelling options provided by passenger cars on an uncongested network. Contemporary availability and affordability of alternative transport modes, as well as contemporary attitudes towards travel are deliberately ignored in this study. Given that urban form may long outlast those contemporary attitude and affordability considerations, we suspect this is a fair exclusion here when evaluating long term impacts of land-use changes. The only assumptions made on travel behaviour are that the likeliness of a trip decreases with travel time, and that people are more likely to make trips to destinations with more inhabitants. These assumptions are all firmly grounded in spatial interaction modelling practice; a practice that has repeatedly been proven to be theoretically sound (23,30) and empirically useful (22,31).

A comparison of LUISA outcomes for Warsaw shows that compact urban development may affect average travel distances: development according to the LUISA scenario may reduce average travel distances with 500 meters by 2030. However, we show that urban densities only partially affect average travel distances; accessibility to distant destinations acts as a counterweight to urban densities. These results thus demonstrate the real challenge of planning for sustainable transport: whenever transport infrastructure is improved, the need for policies to retain high urban densities becomes more stringent. Unfortunately, the results of this section may show that current urban planning instruments do not seem to be able to rise up and meet this challenge. Even in the Netherlands, where compact urban development has been the mainstay of spatial planning policies since the 1980s (32), high accessibility values have greatly offset higher urban densities, and the country's major cities are among the worst-performing in terms of modelled average travel distances. Of course, these results are for cases where only road transport is considered. The environmental results would surely be better if the share of other transport modes such as bicycles and public transport are taken into consideration in Netherlands. In any case, these findings possibly demonstrate that those policies that foster compact urban development may have a very limited effect on curtailing transport demand, if not supported by complementary sustainable transport policy measures such as public transport development, bicycle infrastructure incentives or stringent parking limits. Clearly more research is needed to get a full picture: for example to understand the costs of not doing anything? Furthermore, the usefulness of potential complementary policies is yet to be discovered – for example, policies to promote public transport ridership or use of slow transport modes.

A number of improvements to the average travel distances indicator may be considered. Most importantly, currently continuous trips are being allocated. Thus, although any inhabitant makes the sum of one trip, that value of one trip can be divided over a large number of destinations so that in fact fractions of trips from an origin are allocated to various destinations. This is consistent with the concept that every inhabitant is allowed an equal number of trips, but the simulated travel pattern will only hold if each inhabitant makes an equally very large number of trips. Alternatively, the computation method could be set to allocate trips discretely. This could be done by estimating trip utility and possibly by introducing a random utility component. That way the method essentially answers what the pattern would be if every inhabitant makes only one trip. Another potential improvement concerns transport modes. Currently the relationship between trips and transport modes is left unexplored. If additional information on travel times for other transport mode becomes available, a simple parameterized choice model may be used to obtain potential percentage mode usage for each origin.

Lastly, the indicator allows for a further disaggregation of the modelled trips to Europe's transport networks. Such disaggregation can yield useful information on where energy for transport is being consumed. This is useful for disaggregation works such as done in the EREBILAND project; it may also be useful to map environmental problems related to traffic such as air and noise pollution. This section shows the first results of a transport modelling attempt in which vehicle kilometres travelled on the network are eventually disaggregated to 100 meter grid cells. Further work will be needed to verify the empirical validity of this method and integrate it with interregional traffic flows, such as modelled by the TRANS-TOOLS model.

3. A measure of urban form efficiency with the ease of access to potential public transport services

It is repeatedly noted that urban form can have a substantial impact on public transport ridership (8). Underneath this are the facts that public transport (PT) investments depend very much on land use characteristics and that PT stops generally have a limited geographical reach. Walking distance is an important limiting factor in particular for transport modes that are meant to serve the direct urban area, such as buses. Recent evidence from Australia for instance shows that the majority of bus users live within 500 meter of a bus stop (33). PT is assumed to be a more sustainable option when compared to passenger cars. Given the dependence of PT ridership on urban form, this begs the question of how efficient Europe's cities are for supporting PT services.

Today, promotion of PT in urban areas and concentration of urban development at PT nodes are given high importance. Such policies serve to foster sustainable urban development and transport policies, together with complementary policies that strive for compact city development. Such compact city policies aim at facilitating walking and cycling, easing access to PT services and increasing the share of PT usage. Such compact cities are expected to have several benefits. The most straightforward ones are I) less car dependency and lower emissions, II) less energy consumption, III) higher overall accessibility, and finally IV) preserved green infrastructure in the peripheries. The indicator introduced here is designed to explore how compact European cities are, or, in other words, how efficient European cities are in terms of potential for PT service development and ease of access to PT services. A spatial simulation approach with a number of critical assumptions has been applied for this measure.

This exercise attempts to explore urban form efficiency by recreating minimal public transport system coverage in Europe's cities, in a method governed by three major assumptions:

- The first assumption is that a public transport system with a smaller geographic span is more efficient both from the costs and transport service point of view; thus, a transport system that reaches more people with less PT stops will have higher ridership at lower costs.
- The second assumption is that any public transport system should cover a substantial proportion of a city's population. Preferably, the majority of the population for a more sustainable system.
- The third assumption is that the coverage of public transport stops is limited to easily walkable distances, set at maximum 500 meters.

Given these main assumptions, the indicator introduced here counts the minimum number of possible PT stops that serve at least 80% of a city's population; measures the average distance between these PT stops; and counts the inhabitants that those minimum number of PT stops serve. Hence, cities that require less PT stops, cities with PT stops that are closer to each other, and cities with PT stops that separately serve more inhabitants are considered as more efficient for the potential development of PT services. On the contrary, cities that require more PT stops, or cities with PT stops with greater distances in between, or PT stops that separately serve less inhabitants are considered as less efficient in terms of urban form and ease of access to potential PT services.

3.1. Definition of the indicator

The method for the indicator is based on a 100 m population grid. Each city, in this case Functional Urban Areas (FUAs), is a separate subset of 100 m grids. In each iteration the method allocates one public transport stop to the optimal place (the central pixel of the most populated catchment area) in a city. To do so it searches the whole city's surface and attempts to find the pixel with maximum number of inhabitants within 500 meters radius. An already covered inhabitant by a PT stop is not counted again for the next PT stop allocations, so that the optimal location for the next PT stop is different from the previous ones. The only input to the indicator is a population grid which can be defined as a matrix at iteration zero *as,* P_{ij}^{0}.

The procedure starts from the initial cell, say origin, 0_{mn}, m being the row and n being the column numbers of the cell like the i and j in the population matrix. Then determining the catchment area for the origin cell using the 500 meters distance criterion, with a spatial weight matrix, $W^{mn}{}_{ij}$, which in turn is defined as:

$$W^{mn}{}_{ij} = \begin{cases} 1 \; if \; Distance(O_{mn} \; and \; D_{ij}) \leq 500m \\ \qquad\qquad 0 \; otherwise \end{cases} \tag{6}$$

It is static, not changes in each iteration and measures the distance between the origin cell 0_{mn} and all other destination cells D_{ij}. The catchment area populations, $CP^{mn}{}_{ij}{}^{r}$, and the total population, CP^{mnr}, at iteration r, for the origin cell then can be defined using the distance and population matrixes as:

$$CP^{mn}{}_{ij}{}^{r} = W^{mn}{}_{ij} P_{ij}{}^{r} \tag{7}$$

$$CP^{mnr} = \sum CP^{mn}{}_{ij}{}^{r} \tag{8}$$

If the equations 6, 7 and 8 repeated for all cells taking them as origins, a matrix, CP_{ij}^{r}, that includes the total populations, within 500 meters for each cell as an origin, can be achieved via:

$$CP_{i=m,j=n}{}^{r} = CP^{mnr} \tag{9}$$

Finding the maximum of CP_{ij}^{r} matrix gives us the best PT stop allocation as selected cell at iteration r. Then the coordinates of the selection(s) can be recorded to the vectors, SEL_{r1} and SEL_{r2} as following:

$$SEL_{r,1:2} = while \; CP_{ij}{}^{r} = \max(CP_{ij}{}^{r}) \; \begin{matrix} SEL_{r1} = i \\ SEL_{r2} = j \end{matrix} \tag{10}$$

The procedure continues up until to a threshold. The 80% of population should be covered with the selected PT stops. This can be achieved via calculating the covered population, Pop^{r}, and the share of covered population by the selected PT stops, $Spop^{r}$, which are increasing in each iteration:

$$maxCP^{r} = \max(CP_{ij}{}^{r}) \tag{11}$$

$$Pop^{0} = maxCP^{0} \tag{12}$$

$$Pop^{r} = (Pop^{r-1} + maxCP^{r}) \tag{13}$$

$$SPop^{r} = (Pop^{r})/(\sum P_{ij}{}^{0}) \tag{14}$$

The procedures from equations 6 to 14 are repeated with increasing r until $Spop^{r}<0.80$, at which point the procedure stops. Finally, in order to remove the already counted population in any r+1 allocation, the population of cells within the catchment area of a selected PT stop, $CP^{mn}{}_{ij}$, should be subtracted from the initial population matrix, P_{ij}^{r}:

$$P_{ij}{}^{r+1} = P_{ij}{}^{r} - CP^{mn}{}_{ij}{}^{r} \tag{15}$$

Here m is the row and n is the column of the selected PT stop in iteration r, achieved respectively via SEL_{r1} and SEL_{r2} in equation 10. The subtracted population matrix then serves in equation 7 to calculate new catchment areas population and ensures that the best option for a PT stop is different than the previous ones.

After the search for new public stop sites is ended with a final iteration r, the average distance, *AvrD*, between the public transport stops, where the coordinates were recorded to the columns of *SEL,* is computed as:

$$AvrD = \frac{\sum Distance(SEL_{i.} \; and \; SEL_{j.})}{(r^{2}-r)} \tag{16}$$

Finally the urban efficiency indicator (UFE) for a city is computed in a normalized way so that:

$$UFE = \frac{(Pop)}{(PTS)(AvrD)} \tag{17}$$

Where *PTS* is the number of PT Stops that serve 80% of the population, it is equal to the number of iterations, *r*; *AvrD* stands for the average distance between the PT Stops; and finally, the variable *Pop* stands for the total population that the allocated PT Stops serve (80% of overall total) as achieved with the equation 13. The consequence is that the urban efficiency indicator computes number of public transport stops and their underlying distance relative to city population. Thus, if population is held equal, a higher number of transport stops or a higher average distance between those stops leads to lower efficiency. If transport stops and average distance between stops is held equal, a lower population number will lead to a lower efficiency.

3.2. Results

The indicator has been computed for all FUAs in Europe as a pilot study, using the EUROSTAT Population Grid for 2011 (19). The grid population counts at 1 km resolution. Since the algorithm runs at 100 m, the EUROSTAT grid was equally resampled to 100 m grids. Table 3 introduces the results, a classification of Europe's cities (FUAs) based on the Urban Form Efficiency (UFE) indicator measured via ease of access to potential PT services. As mentioned earlier, the method first identifies the minimum number of PT stops that could serve 80% of a city's total population, and second computes the average distance between the identified PT stops. It finally normalizes multiplication of these two values with the population that is served within the city. If the majority (80% of the population) of a city can be served with few PT stops and these stops are close to each other, this city has a more efficient urban form. On the contrary, if a city is served with a large number of PT stops and the average distance among these PT stops is high, the city has a less efficient urban form.

A further analysis has classified FUAs into five groups according to a novel classification method that takes into account a FUA's geographical size and its population distribution. In this classification method circles are drawn around a FUA's centre and subsequently the population in the underlying population grid is summed to that circle. This is done repeatedly with different circle sizes ranging from 10 to 50 kilometers. The circle that contains at least as many people as are recorded in the FUA is chosen; the FUA is subsequently classified into the group of FUAs with similar circle sizes. The indicator is designed to make comparisons within groups of similar cities, like Paris vs London or Rotterdam vs Porto and is a useful tool to group heterogeneous units into comparable groups, regardless of geography, and relatively independent of modifiable areal unit problems caused by the delineation of areal units (34). It can be used with different units of measurement, such as FUAs or LAU2 zones. Which city belongs to which group can be seen in the Table 3. The 20th percentiles are taken as the changing point for each group of UFE. Table 3 indicates FUAs in a descending order from high to low urban form efficiency.

As indicated in the table and in Figure 9, the cities (FUAs) in Spain, Greece, Bulgaria, Romania and Lithuania are mostly with very high urban form efficiency compared to the others. In other words, the cities in these countries are more compact considering the distribution of population and ease of access to potential PT services. The countries including the United Kingdom, Croatia, the Netherlands and Italy have cities with mostly very high and high urban efficiencies. On the other hand, majority of the cities in countries like Denmark, Belgium, France, Germany and Poland have low or very low urban form efficiency if the distribution of population across the territory and the ease of access to potential PT services are taken into consideration.

Table 3: Urban form efficiency with the ease of access to potential public transport services – classification by FUAs.

Size of Cities (Functional Urban Areas)

Urban Form Efficiency with the Ease of Access to Potential PT Services

	Very Small	Small	Moderate	Large	Very Large
Very High	Talavera de la Reina, Melilla, Ceuta, Narva, Lugo, Brăila, Botosani, Cáceres, Ciudad Real, Craiova, …, Cádiz, Alytus, Buzau, Avilés, Girona, Elda, Annemasse, Algeciras, Ploiesti, Manresa, Puerto de Santa María	Burgos, Bucureşti, Valencia, Thessaloniki, Logroño, Salamanca … Rotterdam, Siracusa, Trieste, Livorno, Bristol, Liverpool …	Zaragoza, Albacete, Pamplona, Valladolid, Córdoba, Bilbao, Vitoria/Gasteiz, Sevilla, Varna, Palermo, Málaga, Genova, Granada, Napoli, Białystok, Torino, León, Cagliari, Marbella, Taranto, Amsterdam, Milano, Daugavpils, Plovdiv, Panevėžys, Malmö, West Midlands urban rea, Nice, Katowice, Manchester, Wrocław	København Athina Mallorca Marseille Vilnius Gdańsk Lisboa Glasgow	Madrid Barcelona Paris Sofia Berlin Tallinn
High	Guadalajara, Ferrol, Satu Mare, Bacău, Inowrocław, Luton, Irun, Călăraşi, Târgu Mureş, Katwijk, Delft, Kalamata, Setúbal, Plymouth, …, Vidin, Darlington, Caserta, Swindon, Frankfurt, Piatra Neamţ, Leiden	North East Lincolnshire, Middlesbrough, Bournemouth, Newcastle, Lille, Sliven … Porto, Köln, Portsmouth, Utrecht, Nottingham, Leeds, Düsseldorf, Kirklees, Lecce, Eindhoven, Derby,	Santander, Burgas, Edinburgh, Bydgoszcz, Bratislava, Toulon, Frankfurt am Main, Kingston upon Hull, Leicester, Cardiff, Sassari, Tampere, Montpellier, Brussels, Norrköping, Hannover, Nürnberg, Olsztyn, Bologna, Grenoble, Västerås, Szeged, Turku, Innsbruck, Perpignan, Debrecen, Leipzig, Ioannina, Košice, Nancy	Stuttgart Tartu Lyon Toulouse Grad Zagreb Split Poznań	Stockholm London Roma Wien Dublin Warszawa
Moderate	Bârlad, Northampton, Peterborough, Veliko Tarnovo, Gloucester, Cheltenham, Pescara, Benidorm, Oxford, Southampton, …, Bradford, Savona, Reading, Milton Keynes, Warwick, Alkmaar, Crawley, Prato, Nijmegen, Worcester	Shumen, Most, Kassel, La Spezia, Kavala, Darmstadt … Middelburg, Pisa, Verona, Metz, Helsingborg … Reutlingen, Modena, Liège, Roosendaal, Salzburg, Koblenz	Exeter, Lahti, Münster, Karlsruhe, Clermont-Ferrand, Toledo, Ajaccio, Reims, Strasbourg, Pleven, Magdeburg, Groningen, Venezia, Ostrava, Freiburg im Breisgau, Rouen, Augsburg, Tours, Ljubljana, Plovdiv, Halle an der Saale, Koszalin, Plzeň, Miskolc, Lübeck, Erfurt, Jelgava, Kecskemét, Brest, Dunkerque, Saarbrücken	Bremen Rostock Oulu Bordeaux Jönköping Uppsala Linköping Örebro	Budapest Helsinki Liepāja Aberdeen Hamburg
Low	Pabianice, Deventer, Hilversum, Gouda, Torbay, Krefeld, Torrevieja, Bergamo, Remscheid, Sunderland, …, Chemnitz, Redditch, Solingen, Bielefeld, Viareggio, Brandenburg an der Havel, Acireale	Jastrzębie-Zdrój, Charleroi, Derry, Głogów, Cosenza, Trento … Parma, Trenčín, Aschaffenburg, Lubin, Avignon, Pardubice … Gent, Lorient, Brugge, Pavia, Sant. De Compostela	Norwich, Caen, Saint-Etienne, Angers, Pécs, Oldenburg, Bremerhaven, Ulm, Limoges, Troyes, Le Mans, Linz, Osnabrück, Konstanz, La Rochelle, České Budějovice, Regensburg, Amiens, Würzburg, Székesfehérvár, Osijek, Győr, Luxembourg, Ingolstadt, Potenza, Göttingen, Częstochowa, Châteauroux, Bourges, Nyíregyháza	Brno Kiel Braunschweig-Salz.-Wolfs. Nantes Orléans Dijon Cork	Ruhrgebiet München Praha Umeå Göteborg Kuopio
Very Low	Heerlen, Almelo, Alphen aan den Rijn, Martigues, Roman, Wycombe, Lecco, …, Chesterfield, Como, Varese, Avellino, Kortrijk, Póvoa de Varzim, Biella, Treviso, Pordenone, Guimarães, Viana do Castelo,	Colmar, Braga, Belfort, Hildesheim, Jelenia Góra, Lüneburg … Ferrara, Friedrichshafen, Leuven, Namur, Quimper, Kalisz … Evreux, Zamość, Asti, Nowy Sącz, Viseu	Cottbus, Pau, Besançon, Flensburg, Opole, Kaiserslautern, Siegen, Poitiers, Schweinfurt, Cherbourg, Rosenheim, Kielce, Szombathely, Kempten (Allgäu), Plauen, Slavonski Brod, Stalowa Wola, Görlitz, Fulda, Rzeszów, Saint-Brieuc, Klagenfurt, Bayreuth, Chalon-sur-Saône, Coimbra, Płock, Angoulème, Niort, Tarnów, Maribor, Passau	Graz Schwerin Stralsund Greifswald Rennes Galway Kraków Lublin	Århus Jyväskylä Dresden Odense Aalborg Neubrandenburg

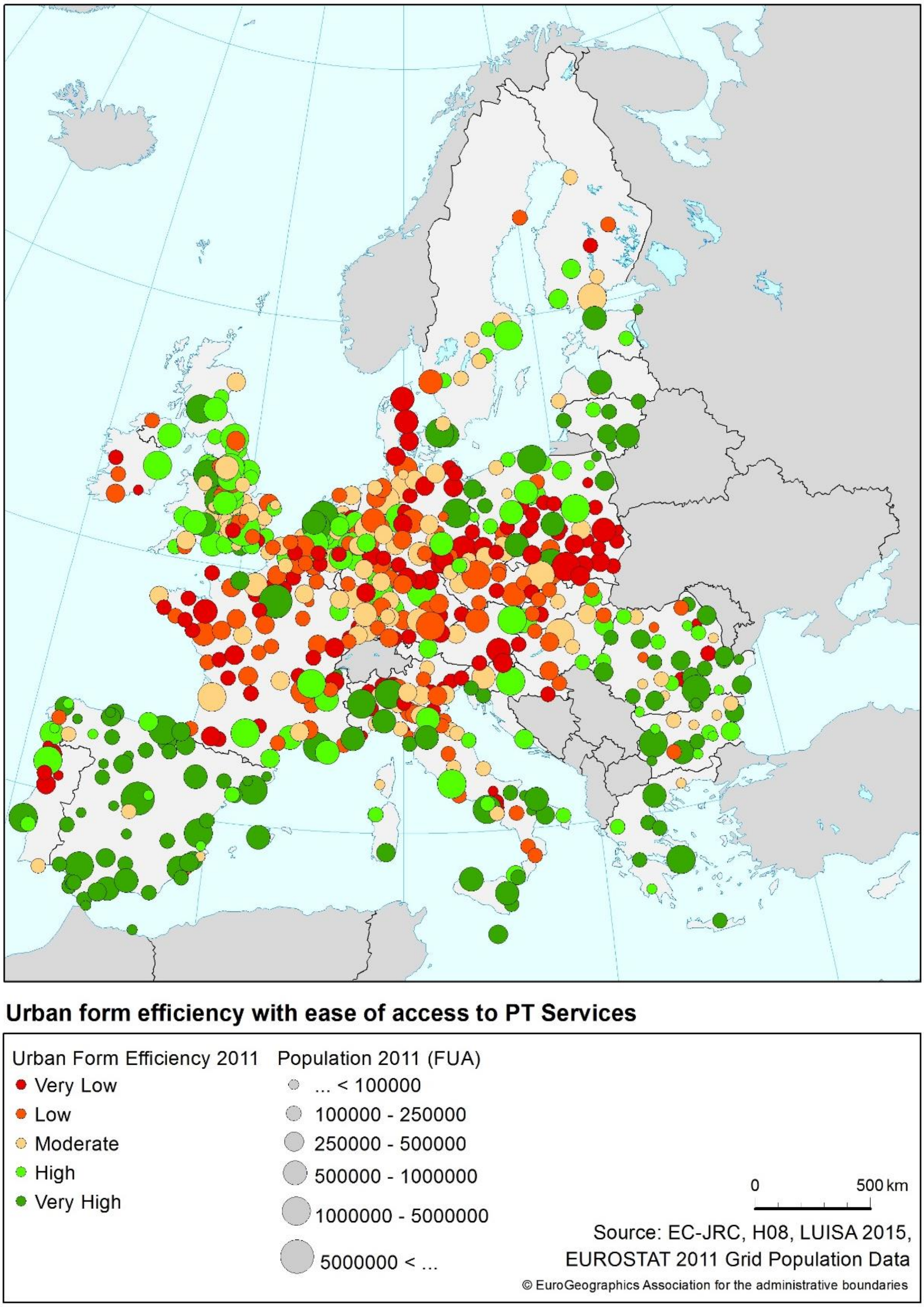


Figure 9: Urban form efficiency with the ease of access to public transport services in Europe's Functional Urban Areas.

4. Conclusions

Sustainable transport for Europe's cities is a key priority for the European Commission. This report has introduced three novel indicators that report on various aspects of sustainable transport. Two of those indicators link urban form with its potential to support sustainable transport, and one indicator builds on the presented simulation work to provide a proxy of the amount of energy consumed on Europe's roads. In all cases, these indicators are based on closed-environment simulation exercises, in which many empirically relevant aspects of travel behaviour are excluded. The choice for such closed-environment simulations is a necessary compromise given, on the one hand, the need to report on highly policy-relevant aspects of transport with a local basis; and on the other hand, a distinct lack of Europe-wide data on travel behaviour on a sufficiently fine spatial resolution. A number of sensitivity analyses will be needed to test the sensitivity of the used indicators for specific parameter settings, and an additional empirical validation will be needed to find to what degree the presented indicators reflect real-world situations. The nature of the presented indicators makes them a useful addition in particular when multiple scenarios or time intervals are compared, so that any systematic bias in the results is cancelled out. Despite the closed-environment nature of the presented indicators, these indicators still add considerably to the body of knowledge on European cities, and will provide useful additions to the toolbox of policy makers that occupy themselves with sustainable transport.

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List of abbreviations and definitions

BAU scenario	Business-as-usual scenario run in LUISA model
Compact scenario	Compact scenario run in LUISA model
EC	European Commission
EREBILAND	“European Regional Energy Balance and Innovation LANDscape” project
FUA	Functional urban area data reporting system
grid cell	One unit in a fine resolution regularly latticed data reporting system
JRC	Joint Research Centre
LUISA	"Land Use-based Integrated Sustainability Assessment" model
NUTS1	1st level of "Nomenclature of Territorial Units for Statistics"
PT	Public Transport
TeleAtlas	Network data provider
TRANS-TOOLS	"TOOLS for TRansport Forecasting ANd Scenario testing" model

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