MEASURING THE IMPACT OF THE TRANS-EUROPEAN ROAD TRANSPORT NETWORK ON THE ACCESSIBILITY OF EUROPEAN URBAN AGGLOMERATIONS

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Abstract

Main text

References

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ABSTRACT
Transport infrastructure investment serves generally as a catalyst for enhanced competitiveness and economic growth through facilitating an overall reduction in travel times and costs. These gains are part of goals of one of the major European Union (EU) infrastructure policy packages, the Trans-European Transport (TEN-T) Network programme.

This study evaluates the benefits of TEN-T in terms of increased accessibility to population (due to reduced travel times) by employing a detailed and up-to-date representation of the entire European road network.

A routing algorithm has been developed to efficiently exploit the high detail and density of the road network available. By using different impedance functions in reaching out opportunities, the proposed methodology compares two measures of accessibility for all major European urban agglomeration considered (695 in total), one baseline measure that considers the TEN-T network as implemented in 2014, and an scenario measure that considers that all TEN-T network is completed. The methodology addresses as well the issue of self-accessibility by considering a weighted travel time of the entire road network within each urban agglomeration.

The results show where the major benefits (accessibility gains) are expected to occur following a full implementation of TEN-T policy. In general, these are to appear in European areas that are still lagging behind in terms of infrastructure investment (Eastern Europe) and in their neighbouring counterparts (Central Europe). The quantitative estimates presented here may prove useful for an eventual review of the focus and priority as regards the not-yet-implemented part of TEN-T policy.

Keywords: Trans-European transport network, Routing on highly-detailed road networks, Urban agglomerations, Population access to opportunities, Self-accessibility assessment
INTRODUCTION

The benefits of transport infrastructure investment include, inter alia, the reduction of travel times and the related generalized costs impinged upon the users of such infrastructure. These cost savings are in general expected to eventually bring about enhanced competiveness and entail other positive effects (e.g. increased safety) on the areas covered, either directly or indirectly, by the investment.

This is also the case as regards one of the major European Union (EU) infrastructure policy packages, the Trans-European Transport (TEN-T) Network programme, conceived as one the main pillars to sustainably achieve economic, social and territorial cohesion amongst all EU regions. The TEN-T programme has invested since the 1990s on several large infrastructure projects, covering all modes of transport, aiming to guarantee the interoperability and efficiency of the European transport system, and in so doing, contribute to fully realize the implementation of the EU Single Market as regards the seamless movement of people and goods. The EU budget for TEN-T for the period 2007-2013 was 8 billion EUR, and this has increased to 24 billion EUR in the current EU budget (period 2014-2020).

As strengthened by the TEN-T Guidelines (EU Regulation 1315/2013/EC) the main scope of EU transport policy is to interconnect national infrastructure networks and ensure their interoperability by removing bottlenecks, improving cross-border connections and overcome technical barriers, hence enhancing accessibility and stimulating economic activity by reducing travel times and costs. In this context several projects covering all transport modes have already been implemented and several are planned in the medium and longer terms (up to 2030).

The focus of the study presented here is on providing quantitative estimates of the expected benefits accruing from road infrastructure investments, particularly in countries where the TEN-T road investment program is still far from being completed. Future extensions include the application to other modes as well as to consider accessibility in relation to infrastructure costs for welfare analysis.

Moreover, as infrastructure investments are central to ensure an efficient and effective transport system, but also to land-use (population dynamics) and regional growth modelling, it is envisaged to complement the descriptive-like methodology of the paper with an integration with relevant modelling platforms employed by the EU and where accessibility plays a key role (e.g. [24], [25] and [26]. The ultimate aim would be to build a comprehensive policy tool to guide where the biggest payoffs from TEN-T for all of Europe are, and building upon previous attempts to describe the inter-linkages between transport investments and the expected geographical structure change of the related social, political and economic systems (see, for instance, [27]).

The effect of infrastructure enhancements on accessibility is a subject widely analysed in the literature (see, for instance, references [1] to [8]). Accessibility measures are commonly classified in the five categories below (presented in ascending order of calculation complexity):

- **Infrastructure-based measures** – they focus on network efficiency (i.e. difference between real and direct (straight) connections. They do not account then for varying land-use patterns or actual travel times between origin and destination.
- **Cumulative-based measures** – they define a priori a threshold value for maximum travel time or distance and then add up all opportunities within the service zone defined by the threshold. They explicitly consider varying land-use patterns and actual travel times but they necessarily treat equally near and far destinations within the service zone.
- **Gravity-based measures** – they complement cumulative-based measures by weighting opportunities (attractiveness of destinations) via an impedance function that discount opportunities with increasing time or distance from the origin.

- **Utility-based measures** – they complement gravity-based measures by incorporating individuals’ perceived utility for a full choice set of travel options. Accessibility is in this case calculated as the expected value of maximum (random) utility, also referred to as log-sum value, among the alternative destinations. Each destination is associated with certain likelihood to be selected depending on its attractiveness (utility) as compared to all the other options.

- **Activity-based measures** – they provide spatiotemporal indexes that describe the level of access to spatially distributed activities, taking into account the location of opportunities, travel times and costs through the network and, very importantly, behavioural factors influencing transport-related decision and normally captured via travel diary data.

A number of formulations within each of the five categories above are discussed in [10], with an elaboration on the major advantages and disadvantages usually attributed to each of them. As repeatedly noted (see, for instance, [8], [13]), even if utility- and activity-based formulations may better reflect individuals’ behaviour, they are normally not that much used in practical applications given the data intensity they entail and, to a lesser extent, the higher elaboration of their output, not always easy to communicate to non-expert audiences.

In this context, the results presented here correspond to the use of gravity-based measures, namely potential accessibility with exponential decay functions. These have been widely used in the literature as a convenient accessibility indicator that is not particularly data intensive but is reasonably easy to compute and able to provide continuous measures taking into account diminished weights for more distant destinations.

**DATASETS**

The methodology herein presented is based on the detailed information on the European road network compiled by the company TomTom and provided with their MultiNet product – the release employed in this paper corresponds to December 2014. This database provides a comprehensive, connected and routable road network for all the European continent (including Turkey and Russia) – this commercial product is the base for the road navigation systems provided by TomTom and precisely for that reason, it includes a thoroughly checked wide set of attributes (such as geometry of the road segments, speed restrictions, free-flow speeds or functional road classes, the latter being a measure of the importance of the road in terms of traffic).

To the best of our knowledge this is the first exercise that uses European-wide TomTom MultiNet data for analysis of accessibility at European level, that is, with routing and travel time calculations across this detailed network.

The detailed road network is integrated with the network attribute data describing the TEN-T network and available from TENtec (the European Commission’s Information System to coordinate and support the TEN-T policy). The version employed corresponds to 2014 and corresponds with the last update of the TENtec data, specifically re-designed to eliminate inconsistencies of previous versions and make the dataset usable for analysis purposes; in particular the main geometry changes have been limited to technical adjustments to better reflect the reality. Moreover, the entire TEN-T road network has been realigned with the help of another commercial (cartography-focused) product, the EuroRegionalMap (ERM) [17].

By comparing the geometry of the TomTom MultiNet database with the updated TENtec network it has been possible to identify the road links which form part of the TEN-T road network.
and with that incorporate attributes such as the type or status of the policy intervention (e.g., already completed, ongoing or planned project). To the best of our knowledge this is the first exercise that uses this improved version of the network by TENtec (mapping of projects into ERM).

As expected, and according to their different scope, the TomTom MultiNet dataset is quite precise in geo-location and rich in details (in order to suit the needs of commercial navigations system) while the TENtec road network is coarser. MultiNet is comprised of over 18 million links, with and average length of 160 meters, leading to a total of approximately 2.85 million kilometres of roads used in the analysis, while TENtec is comprised of 4440 links with a much longer average length per link (over 35 kilometres). Moreover, TomTom MultiNet considers not only TEN-T roads (a significant benefit from the analysis proposed as key connecting roads are also incorporated in the analysis) and contain directional information on the attributes, that is, for two-way links (75% of the total) attributes are compiled for each of the directions, which is another element rendering precision to the routing based on this network.

The matching and flagging of attributes between both network datasets have proven a somewhat rather time-consuming exercise. The main issue has been to accommodate the different grade of precision (and the resulting mismatches) between the two compared geo-databases. In total more than two million links in TomTom have been flagged as being part of the TEN-T road network. Similarly, this pre-processing work has allowed identifying and including in the analysis nearly 500 TEN-T road segments planned but still under study or in any case not yet completed, and so present in the TENtec but missing in the TomTom database.

To give an idea of the cumbersome geo-data pre-processing tasks required for matching both network datasets, and noting that them both are already based on commercial networks, it was identified (especially in some countries) divergences higher than 300 meters between their respective geographical representation of the same roads. This has slightly lengthened the work, as it eventually required manual checks of part of the network – just as an indication, it has been necessary to manually adjust (add/match) more than 5000 road sections.

METHODOLOGY

Based on the resulting integrated network, with specific algorithms developed in MATLAB, it has been possible to calculate the travel times between origins and destinations according to the length of the route and to the free flow speed for each link (i.e. neglecting at this stage the congestion on the roads that could be taken in account in further research developments). In particular the study has considered as destination points all municipalities in Europe (a total of 143205), while the origins have been restricted to Functional Urban Areas (FUAs), i.e. urban agglomeration areas, as defined in [15] (a total of 695 in Europe). Practically, a FUA consists of a city and its related commuting zone.

The study considers as origins the 695 FUAs existent in EU28 (plus Switzerland, Norway and Iceland) and which are comprised of a total of over 38000 Local Administrative Units and covering almost 60% of European population. An optimized MATLAB routine calculates the travel times along the shortest path [18] from each FUA to each municipality in Europe (with an actual computing time for each origin of approximately 30 seconds). These travel times represent key elements in our accessibility measure.

Bearing in mind the wide range of accessibility indicators discussed in the literature and employed to inform policy-making and evaluate transport infrastructure projects performance, etc. (see introduction), and considering that the focus of this paper is on presenting first results for the evaluation of the benefits associated with the completion of the TEN-T network, the approach
chosen is to measure accessibility via a gravity-type (potential accessibility) formulation. This is essentially the combination of two factors, attractiveness (representing activities/opportunities reachable from a given origin) and impedance (representing the effort, in terms of time, distance, cost, etc. needed to reach them), that is:

\[
a^m_i = \sum_{j \in \Omega} \left( w_j \cdot f(c^m_{ij}) \right), \quad \forall i \in \Theta
\]  

where:

- \( a^m_i \) is the accessibility by mode \( m \) (road) for a representative individual at origin \( i \),
- \( w_j \) is the opportunities/activities available at destination \( j \) (population),
- \( f \) is the impedance function,
- \( c^m_{ij} \) is the generalized cost to reach destination \( j \) from origin \( i \) by mode \( m \),
- \( \Theta \) is the set of all origins considered in the analysis, and
- \( \Omega_i \) is the set of all destinations reachable from origin \( i \).

Notice that in practice the presented formula is just a weighted sum of the set of activities reachable from origin \( i \), the weights being the friction to overcome to reach each destination \( j \).

The measure of opportunities and activities at each destination is the population at municipality level (2011 values). Future work will include an extension to compare the effects when GDP or employment levels are used instead, this should contribute for instance to the debate on the effects of accessibility on shaping urban settings (e.g. compact versus sprawled urban forms) and on the measurement of convergence towards resource efficiency.

As regards the impedance function \( f \), its exact definition is of key importance as it will clearly impact the obtained results. Several forms of distance decay function have been proposed in the literature, as well as contributions elaborating on the shortcomings and advantages of each of them (e.g. [20] and [9]). The results shown in this paper employ a negative exponential function of the travel time component of the total generalized cost, in line with common practice (see, for instance, [30]):

\[
f(t_{ij}) = \exp\left(-b \cdot t_{ij}\right)
\]  

The value assumed (calibrated) for the decay parameter, i.e. \( b \), very importantly, defines the shape of the impedance function, with lower values of \( b \) representing slow decay functions that assign a certain weight also to longer travel times, and so taking into account interactions and opportunities available between municipalities that are not close to each other, which is of particular relevance, for instance, for the study of freight transport or case of leisure-type travel.

On the contrary, higher values for the decay parameter \( b \) represent steeper impedance functions and a reduction on the size of the surrounding area with some impact on the accessibility of a given zone. These higher values typically represent patterns associated with shorter-range travel (e.g. commuting, and daily home-work trips).

At this stage it has not yet been possible to properly calibrate the decay parameter based on available traffic data for the whole Europe, and then the focus is on predefined values. Further developments of this research will consider a calibration procedure that aligns the decay function to those impedance function governing traffic patterns between urban agglomerations. Other
studies propose calibration procedure of the discriminant parameters based on actual traffic data in the study area (e.g. [7] and [21]).

For the purposes of the results presented in this paper three different decay parameters are employed, each of them assumes that 90% of the weight is given to opportunities that arise within a time-zone defined by a given threshold. These thresholds have been defined as 2 hours and 30 minutes (steeper decay) to represent short-range trips, e.g. commuting, urban freight deliveries, etc., 5 hours (medium decay) to represent medium-range trips, and 10 hours (slow or flatter decay) to represent long-range trips, e.g. freight, leisure-type, etc. It would indeed appear that a 2 hours and 30 minutes is high to represent a commuting trip. In fact, this threshold represents a whole catchment area that tries to capture all types of short-range travelling, with 50% of the weight assigned to trips below 45 minutes, 60% of the weight for those below 30 minutes, etc. The same applies to the other decay functions.

Each major urban agglomeration considered in the analysis (695 in total, representing over 300 million inhabitants), also referred to as Functional Urban Areas (FUAs), is comprised of an average of fifty municipalities. The adopted approach calculates the minimum travel time and resulting accessibility measure from the population-weighted centroid of each urban agglomeration to the (population-weighted) centroids of all municipalities in Europe (143205 destinations, representing over 800 million inhabitants). This includes municipalities that are part of urban agglomerations (over 30000), hence partially solving the self-potential issue arising in accessibility analyses (further elaboration below). The resulting measure provides then an accessibility per (representative) inhabitant for each urban agglomeration.

Self-accessibility

The self-potential issue consists in the difficulty to measure the total interaction opportunities within the analysed origin zone and scale them to be comparable with (non-self) accessibility, that is, the accessibility from reaching all other destinations from a given origin.

As initially discussed above, the approach adopted in this paper is to calculate self-accessibility for each of the fifty municipalities that exists on average on each the 695 urban agglomerations and then add them up. Moreover, the entire road network of these urban agglomerations is employed in the self-accessibility calculation, this represents a total of over three million kilometres, that is, over 4500 kilometres of roads are used on average per urban agglomeration to calculate its self-accessibility.

Noting that the biases arising from a poorly designed measure of self-accessibility may particular distort results in large urban areas [16], or when using steeper decay functions [7] – the approach proposed in this study have thoroughly analysed different options. The main procedures studied are the following four (presented in ascending order of specification complexity and required computational intensity):

- **Fixed-value** – constant and predefined values for internal travel times.
- **Density-based** – calculation of intrazonal travel times based exclusively on population and by means of adjusting an econometric model on observed data (e.g. [5])
- **Area-based** – calculation of intrazonal travel distances as a function of its area (e.g. [22], [23]) and corresponding intrazonal travel times derived from employing a representative speed or rather by employing a weighted average speed, with the weighting being based on the length and importance (traffic-wise) of the road segments.
- **Point-to-point** – more thorough account of both network characteristics and the population distribution within a given zone by further disaggregating the zone under study in a number of
lower-level units (e.g. groups of building blocks, detailed postal code areas, or grid-level population maps).

The study presented here calculates the self-accessibility within each major urban agglomeration considered by a combination of area-based and point-to-point approaches.

Firstly, the average internal travelled distance for each municipality in a given urban agglomeration is approximated by means of the widely applied formulation that follows:

\[
d_{ij} = \frac{(\text{area}/\pi)^{1/2}}{2}\tag{4}
\]

The area considered in (4) is the total area of the municipality – that could be further refined by considering built-up areas and a measure of the degree of urbanization for each municipality.

Secondly, average internal travel times for each municipality are calculated by employing a weighted average speed (based on the length and importance of road segments):

\[
t_{ij} = \sum_{s \in \Lambda_i} \left(\frac{d_{ij}}{k_s \cdot m_s \cdot v_s}\right) / \sum_{s \in \Lambda_i} \left(k_s \cdot m_s\right)
\]

where:
- \(t_{ij}\) is the internal travel time for municipality \(i\),
- \(d_{ij}\) is the internal travel distance for municipality \(i\), defined in (4),
- \(k_s\) is the scaling factor for road segment \(s\) (related to its functional road class),
- \(m_s\) is the length of road segment \(s\),
- \(v_s\) is the speed of road segment \(s\), and
- \(\Lambda_i\) is the set of all road segments in municipality \(i\).

Note that the scale factors for each road segment permits a better representation of expected internal travel distances as they depend on the functional road class (FRC) the segment belongs to. This FRC is an attribute in TomTom MultiNet that is based on the importance and traffic supported by the link. Further extensions could consider a refinement of these scaling factors via the calibration of flow-speed curves and at least for a given set of representative urban agglomerations.

In accordance with the previous formulas, the average self-accessibility for urban agglomeration \(I\), comprised of a given number of municipalities \((i)\), is calculated as follows:

\[
a_{\text{self}}^I = \frac{\sum_{i \in I} \left(h_i \cdot \left(h_i \cdot \exp\left(-b \cdot t_{ij}\right)\right)\right)}{\sum_{i \in I} h_i}\tag{6}
\]

where:
- \(a_{\text{self}}^I\) is the self-accessibility for urban agglomeration \(I\),
\( h_i \) is the population of municipality \( i \),
\( b \) is the decay function parameter,
\( t_{ij} \) is the internal travel time in municipality \( i \), defined in (5), and
\( Y_i \) is the set of all municipalities within urban agglomeration \( I \).

Note that this is still a representative measure of the accessibility per inhabitant in a given urban agglomeration, with this person being able to interact with other inhabitants in the agglomeration (attractiveness).

**Total accessibility**

Finally, the gravity-type (potential) total accessibility for all inhabitants in urban agglomeration \( I \) is calculated as the sum of the formulation in (1)-(2) and the self-accessibility formulation in (6), that is, as follows:

\[
A_i^{total} = h_i \cdot (a_i + a_i^{self})
\]

\[
= h_i \cdot \left( \sum_{j \in \Omega, j \neq c_i} w_j \cdot \exp\left(-b \cdot t_{ij}\right) \right) + \frac{\sum_{j \in Y_i} \left( h_i \cdot \left( h_i \cdot \exp\left(-b \cdot t_{ij}\right) \right) \right)}{\sum_{i \in Y_i} h_i} \quad (7)
\]

All the terms in (7) are defined as in equations (1) to (6), and \( c_j \) refers to the municipality that contains the population-weighted centroid of urban agglomeration \( I \).

Note that the first summation in (7) extends to all European municipalities but one, the population-weighted centroid of urban agglomeration \( I \), this means that the summation is also across all municipalities in \( I \) apart from the centroid. As a result, this first summation in (7) does also account for part of the self-accessibility of \( I \), precisely the part that corresponds to the interactions between the centroid and all other municipalities in \( I \). This contributes to a better measurement of self-accessibility, as on average, each agglomeration \( I \) is comprised of approximately 50 municipalities.

The formulation in (7) is applied to evaluate the variations in the accessibility of the 695 urban agglomerations when comparing two scenarios, one that assumes TEN-T implementation as in 2014 and one that considers that all TEN-T road projects are implemented as of 2014 (and not by 2030 as they are currently scheduled).

The information on the TEN-T project status and attributes is from the European Commission TEN-tec information system. For the road interventions planned as upgrades, an increase in free-flow speeds of 10 percent is assumed (up to the applicable maximum speed limit). For projects that are classified as new, the corresponding road segments are assigned the maximum speed limit for highways (assumed to be 120 km/h for all Europe). Very importantly, the incorporation of new/upgraded infrastructure parameters into the detailed road network used to calculate the travel times in the accessibility formulation in (7) has been carried out by only modifying the relevant part of the detailed network, and not the many types of auxiliary road segments that TomTom MultiNet includes to ensure connectivity (e.g. speeds of service roads or roundabouts are not modified).
RESULTS

The results from applying (7) to the baseline and TEN-T completion scenario are presented in two
tables and three maps. The maps refer to the relative change of total values of accessibility, each
one using a different decay function, whereas the tables present both values of total accessibility
and accessibility per inhabitant, and both relative changes and absolute values. The results in the
tables are aggregated by country.

Each decay function is designed to account better for an specific type of infrastructure
impacts, with the steeper, medium and flatter decays fitting best to measure the impacts on,
respectively, short-, medium- and long-distance transport. In order to facilitate the interpretation of
the values in Table 1 and Table 2, the results from using each decay function have been coloured
accordingly.

The results in Table 1 (absolute values for accessibility gains) show that moving from
steeper to flatter decay functions produce an increase in the accessibility measures, this is
somewhat expected given to the majorly long-range corridor-type nature of the TEN-T road
network. Similarly, Table 1 indicates that the ranking of countries does not depend on the
decay/impedance pattern considered, with Central and Western Europe appearing as highly
accessible, unlike Eastern Europe countries and island-based countries.
TABLE 1 Potential accessibility to population (with and without completion of the remaining TEN-T road network) aggregated by country (all decay functions)

<table>
<thead>
<tr>
<th>Country</th>
<th>Population (urban)</th>
<th>Accessibility to population (TEN-T network as in 2014)</th>
<th>Accessibility to population (Completed TEN-T network)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Steep decay (2.5-hour)</td>
<td>Medium decay (5-hour)</td>
</tr>
<tr>
<td>Austria</td>
<td>4,904,366</td>
<td>31,873</td>
<td>120,902</td>
</tr>
<tr>
<td>Belgium</td>
<td>6,541,155</td>
<td>109,278</td>
<td>306,092</td>
</tr>
<tr>
<td>Bulgaria</td>
<td>4,260,692</td>
<td>9,072</td>
<td>38,084</td>
</tr>
<tr>
<td>Croatia</td>
<td>1,997,499</td>
<td>7,339</td>
<td>32,143</td>
</tr>
<tr>
<td>Cyprus</td>
<td>562,124</td>
<td>375</td>
<td>1,129</td>
</tr>
<tr>
<td>Czech Republic</td>
<td>6,341,240</td>
<td>41,677</td>
<td>161,637</td>
</tr>
<tr>
<td>Denmark</td>
<td>3,772,879</td>
<td>11,483</td>
<td>47,992</td>
</tr>
<tr>
<td>Estonia</td>
<td>762,376</td>
<td>950</td>
<td>2,983</td>
</tr>
<tr>
<td>Finland</td>
<td>2,769,963</td>
<td>3,835</td>
<td>9,785</td>
</tr>
<tr>
<td>France</td>
<td>40,570,036</td>
<td>321,924</td>
<td>1,182,249</td>
</tr>
<tr>
<td>Germany</td>
<td>58,765,501</td>
<td>715,584</td>
<td>2,264,325</td>
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<tr>
<td>Greece</td>
<td>5,702,217</td>
<td>17,838</td>
<td>34,398</td>
</tr>
<tr>
<td>Hungary</td>
<td>5,163,671</td>
<td>28,928</td>
<td>97,904</td>
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<td>Ireland</td>
<td>6,246,153</td>
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<tr>
<td>Italy</td>
<td>30,478,993</td>
<td>214,989</td>
<td>605,359</td>
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<tr>
<td>Latvia</td>
<td>994,161</td>
<td>1,698</td>
<td>4,761</td>
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<tr>
<td>Lithuania</td>
<td>1,552,149</td>
<td>1,963</td>
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<tr>
<td>Luxembourg</td>
<td>512,164</td>
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<td>21,558</td>
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<td>Malta</td>
<td>385,687</td>
<td>210</td>
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<tr>
<td>Netherlands</td>
<td>11,751,738</td>
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<td>Sweden</td>
<td>5,335,704</td>
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<td>United Kingdom</td>
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<td>1,300,063</td>
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<td>Switzerland</td>
<td>3,663,448</td>
<td>27,441</td>
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<td>Iceland</td>
<td>245,822</td>
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<td>Norway</td>
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<td>7,830,254</td>
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</tbody>
</table>

Further insight into the comparison between the baseline and TEN-T completion scenario is provided in Table 2, where the relative change in total accessibility and the difference of accessibility per inhabitant are shown.

It can be observed in Table 2 that even if all countries attain gains from TEN-T completion, the relative benefits are significantly higher in Eastern Europe (e.g. Bulgaria, Croatia, Romania, Slovakia, Sweden, Lithuania, Slovenia, Poland, Czech Republic, Hungary) and Denmark. The latter is a particular case for its peninsula-type configuration that brings significant benefits when the completion of TEN-T (upgrades and new links with Sweden and northern Germany) are taken into account. These countries corresponds in general to those with a low percentage of completed TEN-T projects (less than 50%, except Denmark). On the other hand, countries with high percentages of completed projects, mainly Western Europe countries, are expected to have lower accessibility gains.
More specifically, it is worth noticing that higher accessibility gains do not always correspond to the flatter decay function that takes into account also long distance trips. In several countries the completion of TEN-T projects will benefit mainly the short-range (commuting, urban freight deliveries) accessibility, e.g. Bulgaria, Croatia, Czech Republic, Slovakia and Poland. This may be reflecting (amongst other country-specific factors) on a poorer, less complete status for the transport infrastructure in those countries as of 2014.

On the other hand, the results also reflect that flatter decay functions (i.e. accounting also for long-distance trips) positively impacts overall on the countries that are located in more peripheral areas of Europe, e.g. Norway, Sweden, Latvia, Finland, Estonia, Romania, Hungary, Spain, Portugal, Lithuania. These are in some way representing the effectiveness of TEN-T in building bridges with the more centrally-located population areas in Europe, precisely an objective of EU Cohesion Policy.

The right-hand side of Table 2 presents the difference in accessibility per capita. This is a relevant parameter for TEN-T policy design and evaluation as it contextualizes the expected gains. In fact, per capita indicators are part of many core indicators of the EU Cohesion Policy, which is the one supporting TEN-T implementation. For instance, attending to the results in Table 2, completing the TEN-T affecting Croatia accessibility levels (not necessarily only those projects on Croatian territory) should render a higher relative benefit than focusing on completing the TEN-T projects related to Ireland.
Further to the country aggregated results in Table 1 and Table 2, the spatial distribution of the disaggregated results are presented below in Figure 1, Figure 2 and Figure 3. They contain the results for each of the urban agglomerations for which accessibility is calculated (695 in total).

The figures differ only in the travel-time decay function employed. Figure 1, Figure 2 and Figure 3 correspond, respectively, to a steeper, medium and flatter decay function. This implies that 90% of the potentially accessible population is reachable within, respectively, 2h 30min, 5 hours and 10 hours.

The size of the circles for each urban agglomeration are related to their population (then they are identical for the three figures). The colour represents the relative change in accessibility. To make the pattern of accessibility changes easily interpreted (for each separate figure), the scale is based on quantile-type classification (excluding urban agglomerations with changes of less than one percent).
FIGURE 1 Relative change of potential accessibility to population due to the completion of the remaining TEN-T road network (steeper decay function)
FIGURE 2 Relative change of potential accessibility to population due to the completion of the remaining TEN-T road network (medium decay function)
FIGURE 3 Relative change of potential accessibility to population due to the completion of the remaining TEN-T road network (flatter decay function)
The three formulations considered equally show that the major expected impacts of TEN-T completion are to occur in Eastern European countries, that is, those that are in general still in the process of converging towards the relevant EU average economic and social standard, and which find through TEN-T the opening towards (and from) the more developed/populated neighbouring areas of Western Europe.

As previously discussed, different impedance lead to different assessment of results. For instance, many Spanish urban agglomerations, or the majority of British ones, present negligible changes of accessibility (less than 1%) when a short-range trips (i.e. steeper) decay function is considered (Figure 1), whereas the impacts are significantly higher when enlarging the catchment area via less steep (flatter) decay functions (Figure 2 and Figure 3). This indicates that the networks connecting these urban agglomerations at country level largely exist, but not so much those entailing international (long-range) transport.

On the contrary, for many urban agglomerations in the north of Italy, Germany, Poland, Czech Republic or Slovakia, the relative change in accessibility is much higher when only accounting for short-range trips (Figure 1), and not when also including opportunities associated with longer distance trips (Figure 2 and Figure 3). This underlines that TEN-T networks at regional and local levels are still largely to be completed in these areas and then still significant potential benefit for improvement.

There are multiple factors to be considered in the explanation of the spatial distribution of results obtained, these include the country’s current network efficiency (topology-wise and performance/speed-wise), the land-use patterns within the country (i.e. population density and population distribution) and, very importantly, the relative location of a given country as regards the available opportunities (i.e. periphery effects, cross-border barriers effects, etc.). This in any case reinforces the concept that large infrastructure packages such as TEN-T translate into accessibility gains at different geographical levels, with major gains not only arising from better connectivity between (distant) major urban agglomerations, such as country capitals, but also from facilitating enhanced transport linkages between population/activities at regional/local level.

CONCLUSIONS AND FURTHER RESEARCH

The study herein presented is to the best of our knowledge the first pan-European quantitative evaluation of the expected impact on accessibility introduced by a large infrastructure policy package such as TEN-T. The analysis provides quantitative estimates of such impact for all major European urban agglomerations (695 in total, from 31 European countries, representing over 300 million people) and considers all reachable opportunities (population) from them (143205 municipalities, from 43 European countries, representing over 800 million people).

The research is based on the use of highly-detailed data as regards the geometry and characteristics (speeds) of all the European road network (over five million kilometres of roads are considered). These detailed features are elements that guarantee an accurate spatial representation of the case study, eventually ensuring the plausibility and precision of the results obtained. Finally, the computationally efficient routing algorithm developed to this extent renders this whole exercise (and part of the further research discussed below) feasible.

The spatial distribution of enhanced accessibility expected from TEN-T projects completion suggest that the design of such large transport infrastructure package would benefit from considering potential benefits at different geographical levels (country, region and local scale). Estimates are provided that confirm the expected gains from improved long-distance transport (e.g. opening up of better routes to international markets), but also, very importantly,
estimates that quantify the gains that TEN-T completion would generate in terms of better access amongst urban agglomerations at a shorter-range scale (i.e. country or regional level).

These quantitative estimates provided may prove useful for the evaluation of priorities in the completion of the TEN-T network and corresponding (multi-billion) investment still required or even to inform an eventual review of the focus of TEN-T policy.

A number of extensions to the study and further research are foreseen, these include the ones that follow:

- Application of the methodology to non-road modes to develop more comprehensive multimodal accessibility indicators and an eventual integration of them into relevant modelling platforms (e.g. [24], [25] and [26]). This would render an improved analysis of the many inter-linkages between transport infrastructure investments and their spatial impact on the related economic, environmental and social systems.

- Appraisal of the effects on policy recommendations when opportunities are linked to economic importance, employment levels or average income rather than only to population.

- Complement gravity-based measures of accessibility with the (more comprehensive) utility-based measures to test the robustness of the results. This would contribute to the debate on strengths and disadvantages of alternative accessibility indicators to inform large infrastructure policy decision-making.

- Sensitivity analysis of the results as regards the thresholds employed to define the catchment areas in each impedance/decay function employed (i.e. 2.5-hour, 5-hour and 10-hour, respectively), for instance, by calibrating the decay/impedance parameters based on available data on the transport activity matrices produced by generation-attraction models, and/or by considering impedance functions that better characterize the typically demanded (outbound and inbound) trips by passenger purposes and freight services. This could in turn be useful for instance for a further analysis on economic growth implications of potentially skewed accessibility improvements.

- Consider each municipality as an origin instead of only one population-weighted centroid for each urban agglomeration, that is, further refinement of the methodology and algorithms in the study to provide grid-based accessibility measures. These would consider all relevant (populated) cells of a given territorial grid to build accessibility measures for all the territory under study. This would render it feasible to account for accessibility changes on non-urban areas and entail deeper pre-processing of the large incidence matrix employed in routing and a dynamic update in the routing algorithm of the set of reachable relevant destinations in each iteration.

- Application of the methodology to analyse the effects of separate (one by one or in combination to account for related network effects) TEN-T projects or full corridors.

- Complement the accessibility analysis with project investment information in order to link accessibility changes with infrastructure costs and benefits and with that provide estimates of TEN-T related welfare changes at European level.

- Application of the methodology retrospectively in order to provide quantitative estimates of the contribution of TEN-T completed projects to urban agglomerations’ current accessibility values (as of 2014), controlling the separate contribution to accessibility by the historical evolution of population (and/or economic activity) levels and their distribution. This may offer further relevant insight to correlate infrastructure investment with cohesion indicators (economic, social, etc.) and evaluate accordingly the attained EU-level added value.
REFERENCES


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