RAIL TRANSPORT PERFORMANCE IN EUROPE:
Developing a new set of regional and territorial accessibility indicators for rail

Hugo Poelman, Lewis Dijkstra and Linde Ackermans

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ABSTRACT

This paper presents a detailed analysis of rail passenger services using a new accessibility framework developed with the International Transport Forum and the OECD and a near-complete collection of Europe-wide rail timetables. This framework compares the population that you reach by train to the nearby population to measure how well the rail system performs. This analysis starts from the 2 million inhabited grid cells of 1 km² in the EU, EFTA and UK. This detailed information allows us to assess rail services at the national, regional and local level. At the national level, Austria, Denmark and Switzerland have the highest rail transport performance, while Latvia, Lithuania and Romania score lowest. Iceland, Malta and Cyprus do not have any passenger rail services. Cities consistently perform better than towns, suburbs and rural areas in all countries. Some cities, however, score better than others. Large cities with frequent service do well, as do small cities with a fast connection to a nearby large city. Fifty small cities have no rail services during the peak hours. The paper examines average travel time, which includes waiting time, and optimal travel time, which uses the fastest connection and does not include waiting time, to reflect the different type of journeys. It also compares the impact of replacing the short walk to and from the train station with a short bike ride. The bike ride more than doubles the transport performance of the rail system. Given the relatively low cost of provide bicycle infrastructure and promoting active mobility and micro-mobility, including e-bikes and e-scooters, this is likely to be a highly cost-effective way of promoting more rail travel. This paper uses the same approach as the paper on road transport performance (Dijkstra et al., 2019).
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INTRODUCTION

Travel by rail has been growing in the EU-28. It grew from 375 billion passenger km in 2004 to 441 billion passenger km in 2014, an increase of 17%\(^1\). This growth also translated into an increase in the modal share of passenger km from 6.1% to 6.9%. Although this share may seem small, many people in the EU use rail to commute to work, especially in and around the larger cities. In these cities, rail travel helps to reduce congestion, air pollution and greenhouse gas emissions.

In addition, rail can provide a fast connection from city centre to city centre between many cities and thus provide a faster connection than air travel would. The growth of high-speed rail has helped to make these connections even more attractive. Between 2004 and 2014, high-speed rail in the EU grew from 76 to 109 billion passenger km, an increase of 43%. As a result, the share of high-speed rail passenger km over total rail passenger km grew from 20% to 25%.

Despite the growing importance of rail travel, it has been difficult to analyse this mode of transport at a pan-European scale because the data on rail services is highly fragmented and not harmonised. A few years ago, we managed to construct a virtually complete database with the timetables of all passenger trains for 2014. This new source of information was used in several papers, including a paper on the speed and frequency of rail services (Poelman and Ackermans, 2016) and one on cross-border services (Poelman and Ackermans, 2017).

This paper relies on that same data but takes the analysis several steps further. First, it uses a new accessibility framework. This new framework shows how well a particular mode allows people to reach nearby destinations. A companion paper uses this framework for travel by car (Dijkstra et al., 2019). Second, it takes into account trips that require people to switch trains, while the previous papers only considered direct connections. Third, this paper starts from a far more detailed and comprehensive analysis. For all the 2 million inhabited square grid cells of 1 km\(^2\) in the European Union (EU), the European Free Trade Association (EFTA) and the United Kingdom (UK), it calculates how many people can be reached every 15 minutes during the morning and evening peak, which has taken months of calculations.

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\(^1\) EU transport in figures: Statistical pocketbook 2019
1. ACCESSIBILITY: DIFFERENT CONCEPTS AND METHODS

Many different accessibility indicators have been designed and calculated within the EU, (see for example the European Territorial Observation Network (ESPON) study TRAnsport ACCessibility at regional/local scale and patterns in Europe (TRACC)). Two main types of accessibility indicators are used: potential accessibility and absolute accessibility.

Potential accessibility indicators take into account travel time to all destinations within Europe but give greater importance to nearby destinations and less to more remote destinations by using a distance decay function. The choice of that decay function (linear, exponential, logistic, etc.), however, has a significant impact on the results. In addition, the results primarily reflect the spatial distribution of population and not the performance of the road or rail system. As a result, these indicators typically show a very strong core-periphery effect with high values in the core of Europe and lower values at the edges, regardless of the relative accessibility of the transport system.

Absolute accessibility has often been expressed as the volume of opportunities that are within reach, for instance the absolute number of inhabitants or the volume of GDP within a two-hour drive. While this is an important characteristic of accessibility, it ignores destinations just beyond the two-hour limit and does not differentiate within the two-hour range between destinations close by and further away. Also, this indicator mostly reflects the spatial distribution of the destinations and not the performance of the transport system.

These two types of accessibility are usually calculated for a specific geography, such as NUTS regions or cities. This method has the benefit of simplifying the calculations, but it also means that these results cannot be used for a different geography, which limits their use. This also means that the indicators cannot be compared across different geometries because the data and method to calculate accessibility for cities is different from that used for NUTS regions.

1.1 A NEW ACCESSIBILITY FRAMEWORK

This paper uses a new accessibility framework, which has been developed by the European Commission, the International Transport Forum and the OECD (ITF 2019). It relies on three simple metrics that are easy to interpret.

1. Accessibility is the total number of destinations that can be reached within a fixed amount of time. For rail, this depends on the proximity of a rail station, the speed and frequency of rail services and the spatial distribution of the destinations. In this paper, we use a 90-minute threshold with population as the destination, i.e. the accessible population.

2. Proximity is the total number of destinations located within a fixed distance. It captures the spatial distribution of destinations, and depends on planning, policy and investment decisions. In this paper, we calculate the population with a radius of 120 km, i.e. the nearby population.

3. Transport performance is the ratio between accessibility and proximity. It compares the accessible population to the nearby population. In other words, it shows the performance of a transport mode while controlling for the spatial distribution of destinations. This ratio is multiplied by 100. For rail, a ratio of 30 or more means the mode performs well; a ratio close to 0 means the mode performs poorly.

Because this analysis is done using grid cells of 1 km², the results can easily be aggregated by local administrative units, regions, countries, cities or degree of urbanisation without having to change the method or the data. It also means that the values for cities, regions and countries are fully comparable. To capture the experience of an average resident, these three indicators are aggregated using a population-weighted average.

1.2 A BRIEF DESCRIPTION OF THE METHOD

These paragraphs provide a description of the main elements of the method. A more in-depth methodological description can be found in Annex 1 to this paper.

To calculate the accessible population, we needed to identify which stations were connected by a trip of less than 90 minutes and what cells could be reached from each train station. The train timetables allowed us to identify which stations were less than 90 minutes’ travel apart. We identified stations that could be reached within 90 minutes using the fastest connection during peak hours and taking into account the average travel time during peak hours.

For each station we identified which cells could be easily reached on foot, i.e. within a 20-minute walk. We only have to calculate the accessible population for cells within a short walk of a station because it is by definition zero for all the other cells. Each cell within walking distance of a departure station has the same accessible population: the sum of the population within a short walk of all the stations that can be reached within 90 minutes from that departure station. We did the same for a short bike ride.

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2 The schedules include all mainline train services (long-distance, regional and local trains). Some suburban rail services, especially those provided by operators not member of the International Union of Railways (UIC), may not be included in the timetable data. This may lead to an underestimation of accessibility in the areas concerned.

3 For walking, we selected the eight grid cells surrounding the cell with the train station. This corresponds to a square of 3 x 3 km, in other words roughly 1.5 km as the crow flies from the train station.

4 If a cell is within a short walk from multiple train stations, its accessible population will be higher than that of the cells within a short walk of only one of those train stations.

5 For cycling, we selected all grid cells that have their centroid at maximum 3.2 km from the station. This approximates an area that should be easily accessible within 15 minutes by bike.
This method allows the calculation of different scenarios, each presenting a different combination of active mobility mode and rail travel. We calculate the accessible population by assuming that rail travel is (1) preceded and followed by a short walk, (2) preceded by a short bike ride and followed by a short walk, and finally (3) preceded and followed by a short bike ride.

We used two types of travel time (1) the optimal travel time and (2) the average travel time. The optimal travel time is relevant for people who can choose when they leave, i.e. they can take the fastest connection and do not have to wait to board the train. The average travel time takes into account the waiting time before boarding and the speed of the different connections. This reflects the experience of people who cannot choose when they leave, for example because they work fixed hours or go to school.

The combination of three types of trips with two types of travel time leads to a total of six variants, illustrated by Figure 1.

**FIGURE 1:** Scenarios of rail travel time calculations combined with active mobility modes

<table>
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<th>OPTIMAL TRAVEL TIME</th>
<th>AVERAGE TRAVEL TIME</th>
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<td><img src="image3" alt="Scenario 2" /></td>
<td><img src="image4" alt="Scenario 2" /></td>
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<tr>
<td><img src="image5" alt="Scenario 3" /></td>
<td><img src="image6" alt="Scenario 3" /></td>
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</tbody>
</table>

To express the performance of the rail services, we also need a neutral benchmark against which we can benchmark the accessible population. For this purpose, we computed the population living in a circular area of 120-km radius around the point of departure. This is the population that would be reachable if one could travel as the crow flies and without any obstacles, at a speed of 80 km/h.

Finally, by dividing the population accessible within 1.5 h by the population living in an area of 120-km radius around the place of departure (and multiplying the result by 100), we obtain the transport performance.

Figure 2 shows accessibility, proximity and transport performance at the national level. It shows big differences in all indicators. Accessibility by rail is the highest in the UK and almost zero in Latvia and Lithuania, which both have only a few rail lines. Iceland, Cyprus and Malta are not shown as they do not have any rail service. Proximity is highest in the Netherlands and Belgium, two small, dense and highly urbanised countries, while it is lowest in Estonia, Finland and Norway. The highest rail performance, however, is in Switzerland and Denmark.
The reference years used for this analysis depend on the availability of the required datasets. The population grid refers to the year 2011 (census year)\(^6\), while the rail timetables are those that were valid in 2014\(^7\).

Map 1 illustrates the different concepts in the case of Luxembourg. Starting from the city of Luxembourg, the area of 120-km radius zone includes cities like Liège, Metz, Nancy and Saarbrücken. By rail and using the fastest services available, Nancy, Metz and Trier can be reached within 1.5 h, as well as a series of smaller centres in France, Belgium and Germany. By taking into account the waiting times between scheduled train services, fewer destinations, mostly located inside the country, can be reached within 1.5 h.

MAP 1: Stations accessible within 1.5 h and an area of 120-km radius around the city of Luxembourg

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\(^6\) Currently this is the latest reference year for which Europe-wide grid data are available. The next edition of the 1 km\(^2\) population grid will refer to the census year 2021.

\(^7\) Rail timetables refer to October 2014 for most of the countries. For some countries, timetable data refer to 2015. Every attempt has been made to ensure complete network coverage, including major suburban rail networks. Despite these efforts, 100% completeness cannot be ensured.
2. ANALYSING RAIL PERFORMANCE IN EUROPE

2.1 GRID LEVEL RESULTS

Accessibility and transport performance patterns measured at grid-cell level provide a subtle and varied pattern. This is not so surprising given that we are dealing with more than 2 million observations, i.e. the number of populated grid cells in the EU, EFTA and UK. These patterns may be quite hard to capture on small Europe-wide maps\(^8\). A complete and more in-depth exploration of the original results by grid cell is possible using the interactive map viewer that accompanies this paper\(^9\).

In this section, we will mainly discuss the levels of transport performance. In many places in Europe, daily rail accessibility is zero because these places are located beyond walking or cycling distance from any station or stop where rail services are available. Even in areas close to a station, daily accessibility can be very low. This can be due to the absence of any large destinations within a reasonable distance, to the layout and the characteristics of the rail network or to the poor availability or performance of the rail services provided on that network. At the other end of the spectrum, we find grid cells from which up to 12 million people can be reached within 1.5 h, provided the optimal rail schedules are used, combined with a short walk to/from the stations. However, these extremely high values occur in London and similar centres, where there is a high concentration of residential population anyway, making it easier to reach high values of accessibility. Consequently, we need a benchmark against which we can interpret the accessibility values. This benchmark is the proximity of population, shown on Map 2. It is the population living in a circular neighbourhood of 120-km radius around each of the grid cells. This map provides a smoothed pattern of the large population concentrations in Europe.

The highest values of population proximity are found in places surrounded by major agglomerations: between London and the Midlands in the UK, or in the south-east of the Netherlands and the adjacent German areas, all located between the Ruhr area, the Dutch Randstad, Antwerp and Brussels.

\(^8\) For an easier visualisation on small maps the 1 km\(^2\) grid cells have been aggregated to 5 x 5 km cells by computing population-weighted averages of the 1 km\(^2\) metrics.

MAP 2: Proximity: population within a 120-km radius, 2011

Map shows the population weighted average for cells of 5 x 5 km for better visualisation. Analysis was done for 1 x 1 km cells. Sources: REGIO-GIS, Eurostat, JRC

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As shown on Map 3, in optimal circumstances the transport performance of rail trips, combined with a short walk before and/or after the trip, can exceed 25%. Optimal means that the fastest connection available during peak hours is used, without any waiting time before first boarding the train. In other words, this depicts a situation where the traveller adapts his behaviour, in particular the timing of his trip, to the available connections. This assumes the user reaches the departure station just in time to board the fastest train available during peak hours. Hence, this metric indicates the performance of the best available kind of service on a particular connection, yet without giving information about the frequency of such services. Note that this level of accessibility only refers to travel by rail, without any feeder mode such as public transport or car. The travel times observed between stations are only allocated to the populated grid cells in the immediate neighbourhood of the stations, assuming that only a short walk of less than 20 minutes is needed to reach the station. Map 3 shows that decent levels of relative rail accessibility can be found in many places in Germany, the Netherlands, Belgium, the UK, Switzerland, and in and around some other major cities. More than 5 million inhabitants can be reached within 1.5 h from areas in and around Paris, London and the Ruhr area.
MAP 3: Transport performance by rail plus a short walk (optimal travel time)

Population within a 1.5-hour journey / population within a 120-km radius x 100

- 0
- 1.0 - 10
- 10.1 - 15
- 15.1 - 20
- > 20
- Uninhabited
- No data

Map shows the population weighted average for cells of 5 x 5 km for better visualisation. Analysis was done for 1 x 1 km cells.

Sources: REGIO-GIS, Eurostat, UIC, national railway operators

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The influence of the differences in service frequency is reflected in the figures on Map 4. Here we only take into account the population that can be reached within 1.5 h of an average total travel time, including the average waiting time needed before boarding the (first) train. This is a more user-centric approach. It shows the situation where a traveller decides at which time he wants to leave or arrive. Consequently, depending on the availability of rail services at the chosen time of departure, the user will face less or more waiting time before being able to board the train. This indicator provides a more realistic picture as regards the level of service citizens can expect for day-to-day travel.

In comparison to the previous map, we see that the areas where good accessibility can be found have shrunk to only a small set of major agglomerations. High-frequency services offering good relative accessibility are mostly limited to London and Paris and to the largest cities in Germany, Switzerland and Austria. Good performance is also found in areas like the main urban centres of the Netherlands, in Madrid, Copenhagen or Glasgow.

A large difference between the metrics on Maps 3 and 4 indicates a low frequency of efficient rail connections. In other words, fast services are possible in these locations but are quite rare in practice. This may indicate under-use of the existing infrastructure.
MAP 4: Transport performance by rail plus a short walk (average travel time)

Transport performance by rail plus a short walk (average travel time), 2014

Population within a 1.5-h journey / population within a 120-km radius x 100

- 0
- 0.1 - 10
- 10.1 - 15
- 15.1 - 20
- 20.1 - 25
- 25.1 - 35
- 35.1 - 45
- > 45

Uninhabited
No data

Map shows the population weighted average for cells of 5 x 5 km for better visualisation. Analysis was done for 1 x 1 km cells.
Sources: REGIO-GIS, Eurostat, UIC, national railway operators

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The attractiveness of travel by rail obviously not only depends on the speed or the frequency of the services, but also on the possibilities of feeder transport before and after the train trips. In the scenario we just described, rail travel is only combined with a short walk, resulting in a rather minimalistic vision of rail accessibility.

Assessing multimodal accessibility faces additional challenges, especially when considering complementary public transport. Currently, no comprehensive data on bus, tram and metro timetables are available at the European level. Despite this obstacle, we can evaluate the effect of using short bike rides as complementary travel. Such trips could also be done on a (electric) scooter or e-bike. Combining rail and bike improves the levels of accessibility by enlarging the area around the stations that can be reached quickly.

The effect of this combination is shown on Maps 5 and 6. Optimal rail services combined with a short bike ride before and/or after the train ride (Map 5) result in transport performance levels reaching more than 75%, mostly in areas like Berlin, Paris, Madrid and part of London, but also in various places in the north of France where fast connections to Paris are available. Average total travel time, more convenient for day-to-day-travel, combined with a bike ride (Map 6) still results in good levels of performance (more than 60%) in the cities mentioned before, but also in Glasgow and Copenhagen. Under the same scenario, at least 40% of population can be reached from areas in the Netherlands, Rome, Stockholm, Lisbon, Munich and Hamburg. In comparison to average performance by means of rail + walking, combining rail and bike results in a substantial improvement of transport performance, for instance in areas of Warsaw and Budapest, where the increase is often between 15 and 20 percentage points of population in the 120-km radius neighbourhood. Note that these performance levels assume that the traveller uses a bike both before taking the train and once arrived at the destination station. For instance, the user can use a folding bike, a scooter or a bike sharing system.
MAP 5: Transport performance by rail plus short bike rides (optimal travel time)

Transport performance by rail plus a short bike ride (optimal travel time), 2014

Population within a 1.5-h journey / population within a 120-km radius x 100

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<th>Category</th>
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<tr>
<td>0</td>
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<td>0.1 - 10</td>
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<td>&gt; 45</td>
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Map shows the population weighted average for cells of 5 x 5 km for better visualisation. Analysis was done for 1 x 1 km cells.

Sources: REGIO-GIS, Eurostat, UIC, national railway operators

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MAP 6: Transport performance by rail plus short bike rides (average travel time)

Transport performance by rail plus a short bike ride (average travel time), 2014

Population within a 15-h journey / population within a 120-km radius x 100

0  1.0 - 10  10.1 - 20  Uninhabited  20.1 - 25  25.1 - 35  No data  35.1 - 45  > 45

Map shows the population weighted average for cells of 5 x 5 km for better visualisation. Analysis was done for 1 x 1 km cells.

Sources: REGIO-GIS, Eurostat, UIC, national railway operators.
2.2 NATIONAL RESULTS

Rail transport performance in the EU+EFTA+UK is only 5% for average travel time combined with two short walks (Figure 3). Switching the short walks to a short bike ride, however, has a big impact. It increases performance from 5% to 8% with one bike ride and even to 13% with two bike rides. In other words, replacing two short walks with two short bike rides more than doubles the number of people that can be reached by train.

Rail performance using optimal travel time combined with two short walks is higher (9% compared to 5%). Optimal travel time means that a passenger selects the fastest connection and does not have to wait before boarding the train. As a result, that person can reach more stations within 90 minutes and thus can reach more people. Also, for optimal travel time, riding a bike instead of walking makes a big difference. It increases performance in the EU+EFTA+UK from 9% to 14% with one bike ride and to 22% with two bike rides. It should not come as a surprise that in the Netherlands, half the people taking the train ride their bike to and/or from the station (Verkade and Te Brömmelstroet, 2020).

FIGURE 3: Rail transport performance per country for different walk/bike combinations

<table>
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<tr>
<th>EU+EFTA+UK</th>
<th>Average travel time</th>
<th>Optimal travel time</th>
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Population within 1.5 h / population within 120-km radius x 100
- walk+rail+walk
- bike+rail+walk
- bike+rail+bike
Both the rail performance using the average travel time and optimal travel time varies substantially between countries (Figure 3). Most of the Member States that joined in 2004 and after tend to score low to very low on rail performance, while most of the other Member States score better. A few exceptions stand out. Estonia, Hungary and Czechia score moderately, while Ireland and Greece score low.

The impact of replacing a walk by a bike ride varies by country depending on the population density around the train stations. For example, the UK has a lower rail performance with average travel time and two short walks than Austria. However, if one walk is replaced by a bike ride, the UK scores much higher, which implies that the population density around UK train stations is higher than around Austrian ones.

Figures 4 and 5 provide another look at the variety in transport performance by country. The population of each country is classified according to the level of transport performance the inhabitants have at their disposal. Under the most minimalistic scenario, combining average travel time with short walks to/from the stations (Figure 4), at least 10% of population benefits from a performance level of more than 50% in only few countries (Spain, France and Denmark). On the other hand, performance of more than 50% is available to 15.4% of the EU + EFTA + UK population, with shares of more than 25% of population in Norway, Denmark and the UK when using the fastest connections available in combination with bike trips to and from the station (Figure 5).

FIGURE 4: Population by level of transport performance by rail (average travel time) combined with short walks, 2014
FIGURE 5: Population by level of transport performance by rail (optimal travel time) combined with short bike rides, 2014
One can expect higher levels of transport performance if the population is concentrated closer to the point of departure. A straightforward way of examining this population concentration is to compute the share of population in a 60-km radius as a percentage of the population within a 120-km radius. The higher levels of rail transport performance are mostly found in regions where a large share of neighbouring population is found within a 60-km radius (Figure 6).

This is logical, as it will be easier to serve a population nearby within an hour and a half than to provide the same level of accessibility to a population further away. Still, a high population concentration relatively close to the place of departure is by no means a guarantee of high transport performance.

**FIGURE 6:** Relationship between transport performance by rail plus a short walk (optimal travel time) and population concentration around the place of departure, at NUTS 3 level
Because integrated timetable data on all public transport modes in Europe are not yet available, one can only guess what the regional accessibility performance would be when combining rail with other public transport. Nevertheless, an analysis of transport performance in some major urban centres provides some hints. We evaluated the accessibility of population inside these urban centres using public transport schedules (combined with walking if needed) and – alternatively – using cycling. In most of the cities examined, findings suggest transport performance levels by means of public transport to be lower than by means of cycling when considering trips of maximum 30 minutes. Hence, based on these preliminary results, we may assume that levels of regional transport performance provided by a combination of rail and other public transport might be somewhat lower than the levels we find by combining rail and bike.

2.3 REGIONAL RESULTS

While grid data provide the highest level of spatial detail, there is also a clear need for more aggregated indicators, especially at geographical levels, allowing an easy combination with other sources of indicators. In this paragraph, we present results aggregated at the level of NUTS 3 regions. In many areas this level still provides an adequate variety of spatial patterns. Obviously, the same indicators can also be produced at NUTS 2 level or higher. All NUTS regional values are population-weighted averages of the grid data. This means that the accessibility level of each of the grid cells in a particular region is taken into account according to the number of inhabitants living in that grid cell.

In this section we will focus on the NUTS 3 results for transport performance only.

Performance levels by NUTS 3 region are illustrated by the map series 7 and 8, showing six variants of performance metrics. Considering the average total travel time of the services, thus taking into account the frequency of the services, combined with a short walk to/from the stations (Map 7A), only few, mostly urban, regions attain relatively decent levels of accessibility. Accessibility levels lower than 5%, as available in many – even urban – regions, hardly encourage people to envisage rail travel for day-to-day purposes. If we take into account the fastest available travel option, again combined with walking (Map 8A), NUTS 3 regional accessibility reaches values of more than 25% in some regions. Amongst the hotspots are several Swiss regions, Berlin and several other German urban regions, Vienna, Paris, Copenhagen and London and their surroundings, but also a region such as Zaragoza in Spain, because of the presence of efficient links thanks to high-speed train services.

The transport performance can also be improved by combining the train trips with a short bike ride, replacing a short walk. Maps 7B and 8B depict the combinations of a bike ride to the departure station and a walk from the arrival station to the final destination. Performance can be further improved by replacing the walk to the destination with a short bike ride. This scenario is illustrated by Maps 7C and 8C. In average circumstances (Map 7C), this combination results in a transport performance higher than 20% in 201 regions. Top performance levels are then in the 60%+ range.

Finally, combining short bike rides with the fastest available train trips opens a lot more opportunities for efficient day-to-day travelling (Map 8C). Under that scenario, the number of regions with a performance level higher than 20% becomes 455. Combining rail travel with a short bike ride boosts optimal rail transport performance to more than 75% in regions such as Berlin, Paris, Zaragoza, Valladolid, and parts of London. At the lower end of the performance spectrum, combining rail with cycling can quite easily double the accessibility levels in comparison to those reached with a rail plus walking combination.

10 The analysis of accessibility and transport performance in urban centres is described in Poelman, Dijkstra, and Ackermans, 2020.
11 The data annex to this paper provides aggregated values for all NUTS levels.
MAP 7: Transport performance by rail (average travel time) per NUTS 3 region

Transport performance by rail (average travel time) per NUTS 3 region, 2014

A) Walk + rail + walk
B) Bike + rail + walk
C) Bike + rail + bike

Population within a 1.5-h journey / population within a 120-km radius x 100

0 1,000 km

MAP 8: Transport performance by rail (optimal travel time) per NUTS 3 region

Transport performance by rail (optimal travel time) per NUTS 3 region, 2014

A) Walk + rail + walk
B) Bike + rail + walk
C) Bike + rail + bike

Performance using the average travel time including waiting prior to boarding of trips available for departure during morning and evening peak hours.
Sources: REGIO-GIS, UIC, railway operators, Eurostat
2.4 DEGREE OF URBANISATION RESULTS

NUTS regions, while having sound administrative, historical and legal foundations, are not always the appropriate geographical level for depicting the diversity of the European territories. For that reason, specific typologies have been developed\(^\text{12}\), some of which are directly derived from the 1-km² grid level. Hence, our grid-based accessibility analysis is especially convenient for the computation of aggregates at the level of these territorial typologies.

A major grid-based typology is the degree of urbanisation, distinguishing (1) rural areas, (2) towns and suburbs, and (3) cities (urban centres), using a classification based on population size and density\(^\text{13}\). This three-fold typology is already very relevant for the assessment of accessibility levels, but an even better distinction between areas with a dispersed versus a concentrated population is certainly interesting. For that reason, we present results according to a refined degree of urbanisation classification. This typology distinguishes towns from suburbs, and creates three sub-categories of rural areas. These are villages, dispersed rural areas and mostly uninhabited grid cells\(^\text{14}\).

Rail transport performance in optimal circumstances (combined with a short walk) is illustrated in Figure 7. The urban areas with the best accessibility performance are those in Germany, France, Austria, Switzerland and Denmark. The extremely high value for cities in Denmark can be explained by the presence of a dense suburban network in Copenhagen and surroundings. At the other extreme of the graph, rail transport performance is (almost) zero in urban areas of Lithuania, Latvia and Romania. Compared to larger cities, the situation of smaller towns is roughly similar in Luxembourg, Czech Republic, Sweden and Switzerland, but in most other countries these are less well-connected for daily travel.

**FIGURE 7:** Transport performance by rail plus a short walk (optimal travel time), by country and refined degree of urbanisation

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\(^{13}\) For a detailed description of the degree of urbanisation, see Dijkstra and Poelman (2014).

\(^{14}\) See Annex 2 for a description of the refined classification.
Looking at rail transport performance in average circumstances, thus taking into account the effect of the frequency of services, Figure 8 at first glance presents a similar picture, although obviously with lower levels of performance. A closer look reveals differences in the countries’ rankings. Top scores for urban areas are now found (apart from Denmark) in Austria and France, suggesting very good levels of service frequency in and around cities in those countries. The Netherlands and Belgium have almost the same values for urban areas, although Belgium scores much better when looking at optimal connections (see Figure 7). This indicates that services in Belgium provide a better potential connectivity than in the Netherlands, but with lower average frequencies. In practice, the values of Figure 8 are the most relevant for day-to-day travel. Indeed, the attractiveness of rail services for commuting purposes supposes a good frequency of the services. Starting from smaller towns, average rail transport performance still reaches decent levels in Switzerland, Denmark, Austria, Germany, Luxembourg and Sweden.

**FIGURE 8:** Transport performance by rail plus a short walk (average travel time), by country and refined degree of urbanisation
Optimal rail trips combined with short bike rides lead to a relative accessibility of more than 50% in urban centres in Germany, France and Denmark (Figure 9). Smaller towns often benefit from the bike + rail + bike combination, especially in countries like Belgium, Denmark, Germany, Sweden and the UK. This benefit is mostly visible when considering the optimal available connections, but it becomes somewhat less obvious when looking at the average travel times during peak periods (Figure 10).

While gains in performance levels by combining rail with short bike trips are especially striking in urban centres and towns, they are relevant in all kind of territories. This provides arguments in favour of a further development of cycling-friendly infrastructure in and around railway stations.

**FIGURE 9:** Transport performance by rail plus short bike rides (optimal travel time), by country and refined degree of urbanisation

**FIGURE 10:** Transport performance by rail plus short bike rides (average travel time), by country and refined degree of urbanisation
2.5 CITY LEVEL ANALYSIS

The previous section showed that cities consistently outperformed other types of areas. The performance of individual cities, however, also varies (Map 9). Two types of cities score high on rail transport performance: large cities with an extensive rail system (in descending order: Copenhagen, Berlin, Glasgow, Zaragoza, Paris, Madrid, Zürich, London, Barcelona) and smaller cities with a fast connection to a nearby large city (such as Ciudad Real, Reims and Greve-Ishøj). At the other end of the spectrum, the cities in Latvia, Lithuania and Romania all score very low. In fifty, mostly small, cities there are either no trains or no trains during the peak hours we investigated (shown with an empty circle on the map).

MAP 9: Transport performance by rail plus a short walk (optimal travel time) per urban centre, 2014
This data also reveals which city pairs have a fast connection, a slow connection or no connection within 90 minutes. In total, 18 city pairs have a connection speed over 150 km/h (Table 1). They are located in France, Italy, Spain, Germany and the UK. There is only one cross border connection: Paris-Brussels.

### TABLE 1: City pairs with a rail connection of at least 150 km/h (only cities with at least 250000 inhabitants)

<table>
<thead>
<tr>
<th>City pair (larger)</th>
<th>City pair (smaller)</th>
<th>Straight line speed (km/hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paris</td>
<td>Lille</td>
<td>202</td>
</tr>
<tr>
<td>Milano</td>
<td>Torino</td>
<td>198</td>
</tr>
<tr>
<td>Milano</td>
<td>Bologna</td>
<td>197</td>
</tr>
<tr>
<td>Madrid</td>
<td>Zaragoza</td>
<td>188</td>
</tr>
<tr>
<td>Paris</td>
<td>Bruxelles / Brussel</td>
<td>182</td>
</tr>
<tr>
<td>Barcelona</td>
<td>Zaragoza</td>
<td>175</td>
</tr>
<tr>
<td>Berlin</td>
<td>Hannover</td>
<td>172</td>
</tr>
<tr>
<td>Málaga</td>
<td>Córdoba</td>
<td>168</td>
</tr>
<tr>
<td>London</td>
<td>Lille</td>
<td>168</td>
</tr>
<tr>
<td>Napoli</td>
<td>Roma</td>
<td>167</td>
</tr>
<tr>
<td>Sevilla</td>
<td>Córdoba</td>
<td>167</td>
</tr>
<tr>
<td>Roma</td>
<td>Firenze</td>
<td>161</td>
</tr>
<tr>
<td>Bruxelles / Brussel</td>
<td>Lille</td>
<td>159</td>
</tr>
<tr>
<td>Bologna</td>
<td>Busto Arsizio</td>
<td>159</td>
</tr>
<tr>
<td>Madrid</td>
<td>Valladolid</td>
<td>157</td>
</tr>
<tr>
<td>London</td>
<td>Coventry</td>
<td>156</td>
</tr>
<tr>
<td>London</td>
<td>Newcastle-under-Lyme</td>
<td>151</td>
</tr>
<tr>
<td>Stuttgart</td>
<td>Mannheim/Ludwigshafen</td>
<td>150</td>
</tr>
</tbody>
</table>

Note: Only cities with at least 250000 inhabitants were considered.
Only ten city pairs have a rail connection that is slower than 60 km/h (Table 2). They are all located in the UK.

**TABLE 2:** City pairs with a rail connection of less than 60 km/h

<table>
<thead>
<tr>
<th>City pair (larger)</th>
<th>City pair (smaller)</th>
<th>Straight line speed (km/hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greater Nottingham</td>
<td>Coventry</td>
<td>47</td>
</tr>
<tr>
<td>Leicester</td>
<td>Coventry</td>
<td>50</td>
</tr>
<tr>
<td>Rotherham</td>
<td>Newcastle-under-Lyme</td>
<td>52</td>
</tr>
<tr>
<td>Portsmouth</td>
<td>Southampton</td>
<td>54</td>
</tr>
<tr>
<td>Southampton</td>
<td>Brighton</td>
<td>54</td>
</tr>
<tr>
<td>Greater Manchester</td>
<td>Greater Nottingham</td>
<td>56</td>
</tr>
<tr>
<td>Tyneside conurbation</td>
<td>Stockton-on-Tees</td>
<td>57</td>
</tr>
<tr>
<td>Portsmouth</td>
<td>Bournemouth</td>
<td>57</td>
</tr>
<tr>
<td>Greater Nottingham</td>
<td>Newcastle-under-Lyme</td>
<td>57</td>
</tr>
<tr>
<td>Liverpool</td>
<td>Rotherham</td>
<td>59</td>
</tr>
</tbody>
</table>

Note: Only cities with at least 250 000 inhabitants that are less than 120 km apart were considered. Connections between stations that are less than 25 km apart were excluded.

**TABLE 3:** City pairs with no rail connection within 90 minutes

<table>
<thead>
<tr>
<th>City pair (larger)</th>
<th>City pair (smaller)</th>
<th>Straight line distance (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Górniośląski Związek Metropolitalny</td>
<td>Kraków</td>
<td>75</td>
</tr>
<tr>
<td>Málaga</td>
<td>Granada</td>
<td>86</td>
</tr>
<tr>
<td>Vilnius</td>
<td>Kaunas</td>
<td>89</td>
</tr>
<tr>
<td>Bristol</td>
<td>Bournemouth</td>
<td>93</td>
</tr>
<tr>
<td>Brighton</td>
<td>Southend-on-Sea</td>
<td>99</td>
</tr>
<tr>
<td>Bristol</td>
<td>Southampton</td>
<td>102</td>
</tr>
<tr>
<td>Stockton-on-Tees</td>
<td>Kingston-upon-Hull</td>
<td>105</td>
</tr>
<tr>
<td>Greater Nottingham</td>
<td>Kingston-upon-Hull</td>
<td>106</td>
</tr>
<tr>
<td>Poznań</td>
<td>Bydgoszcz</td>
<td>109</td>
</tr>
<tr>
<td>Lyon</td>
<td>Genève</td>
<td>113</td>
</tr>
<tr>
<td>Wien</td>
<td>Brno</td>
<td>114</td>
</tr>
<tr>
<td>Porto</td>
<td>Vigo</td>
<td>118</td>
</tr>
<tr>
<td>Genève</td>
<td>Grenoble</td>
<td>118</td>
</tr>
<tr>
<td>Warszawa</td>
<td>Łódź</td>
<td>119</td>
</tr>
<tr>
<td>Praha</td>
<td>Dresden</td>
<td>120</td>
</tr>
</tbody>
</table>

Note: Only cities with at least 250 000 inhabitants that are less than 120 km apart were considered.
The city level data allows us to test to what extent rail performance depends on the extent of the rail network. A simple comparison between the availability of rail networks around cities and the level of rail transport performance (Figure 11) shows transport performance levels do not depend on the length of the network when taking into account population and area. For instance, both Copenhagen and Prague have a railway length index around 200% of the urban centre average but from Prague, 26% of neighbouring population is accessible, while from Copenhagen, performance reaches 65%. Hence, around Copenhagen the available network provides better accessibility services than the network around Prague. Further analysis of this relationship could be interesting, for instance taking into account the actual characteristics of the network such as the presence of double track railways versus single track or the level of electrification. Information about the operational maximum speed of the railway lines would also help in interpreting the differences in transport performance.

**FIGURE 11:** Relationship between transport performance and railway network density around urban centres

– Bubble size represents urban centre population - railway length relative to surface and population

**Note:** The railway length index is the average of the network length in an area of 120-km radius around the city centroid divided by the population and that same network length divided by the land area of that circle.
High levels of transport performance from within urban centres usually occur where the population is quite concentrated in areas close to the centre of the city. Figure 12 shows that cities with a high distance to the population tend to have a lower rail transport performance. For example, Madrid has a high performance (68%) and its average distance to population is less than 25 km. Nevertheless, the distance to population only explains a quarter of the variation in the rail performance (an R square of 0.27). Cities such as Copenhagen, Glasgow and Berlin combine a high transport performance with a distance to population of around 40 km. Conversely, other cities with a similar distance to population (between 30 and 40 km) only reach moderate (Rome, Tallinn and Lisbon) or low (Naples) rail transport performance.

A combined analysis of population concentration, railway network characteristics and transport performance could provide further insights into opportunities for improvement of rail accessibility and performance levels.

**FIGURE 12:** Transport performance by rail plus short bike rides (average travel time) and average distance to population in the neighbourhood of urban centres.

Note: Distance to population is the average of the straight-line distances to each of the populated grid cells within a 120-km radius, whereby each of these cells is weighted by their residential population.
3. CONCLUSIONS

This paper presents a new approach to measure rail accessibility. By comparing how many people can be reached by train to the number of people nearby, we measure and compare rail transport performance across countries, regions and territories. It reveals wide disparities. Most western Member States score better, as do capital regions and cities.

Working with very detailed data brings big computational challenges, but also substantial benefits. The results can easily be aggregated to municipalities, regions and countries. Therefore, the same data can feed debates at the EU, national, regional and local levels.

Compared to road accessibility, rail accessibility is more complex. We produced indicators for optimal and average travel times as well as for trips combined with a short walk and a short bike ride. These different indicators speak to the experience of different types of users. The focus of this paper is on a return trip that can be completed in a day, but the same approach could also be used for longer or shorter trips.

The goal of this paper was to provide a new set of accessibility and transport performance metrics. They are intended to support the assessment of investment needs in regions, cities and territories. To get the full picture, they should be combined with a description of the spatial distribution of population and activities, the geography and terrain of the areas and characteristics of the rail network. This combination can show whether the priority should be:

a) a better use of existing infrastructure,
b) upgrading of the infrastructure,
c) measures favouring densification of land use around train stations and limiting urban sprawl or
d) promoting and facilitating cycling to the train station.

The analysis has shown that, when each walk to the station is replaced with a short bike ride, rail transport performance increases by 50%. Given that bicycle lanes, paths and parking tend to be inexpensive, promoting cycling and other micro-mobility must be a cost-effective way of improving rail transport performance.

This paper provides a snapshot of rail accessibility in 2014. We aim to publish an update in 2020 using the timetables for 2019 and population data for 2018. This will show if rail transport performance has improved or deteriorated. This analysis currently demands a large amount of time. Three changes are needed to speed it up. First, comprehensive annual rail data in a standardised, machine-readable format should be available. a new legal framework provides that this data should be collected, but it does not specify who is allowed to access or use this data. Second, population grid data should be updated annually, which Eurostat is proposing to do from 2024 onwards. Additional demographic and socio-economic variables, such as day-time population and/or workplace-based employment, would be worth being taken into account. Third, more powerful IT tools and infrastructure are needed. Currently, running this analysis takes multiple months. Together with the JRC, we are exploring methods to speed up this analysis. In addition, reliable georeferenced data on the infrastructure characteristics of the railway network could provide insights as to why performance is low on certain routes. Furthermore, fully integrated data on public transport services would allow an analysis of multi-modal accessibility, for instance by combining rail services data with urban public transport.

In short, better data and accompanying analysis opportunities will be able to provide relevant evidence for policy guidance and implementation at European, national, regional and local levels.

ANNEX 1 - METHODOLOGICAL DESCRIPTION

DATA SOURCES

The analysis used three major input datasets: a population grid, the location of the stations and comprehensive data on passenger rail services.

Population by 1-km² grid cell was provided by the Eurostat GEOSTAT 2011 population grid.16 This grid is based on georeferenced census results or address-based population registers whenever available, complemented by disaggregated data where needed. It has been enhanced by adding 1 km² population estimates for some additional countries.17 For subsequent steps in the workflow we needed a point layer representing the population values of the grid. Hence, we have produced grid cell centroid points, each having a unique identifier and the grid cell population figure. This point layer can easily be overlaid with boundary datasets or with data from other grids.

For passenger rail services, the location of all stations and stops was needed, accompanied by complete timetable data referring to a particular working day. Comprehensive data covering the whole of the EU + EFTA + UK are not yet available, although data on most of the services can be found in internal UIC databases. Intensive data integration, enrichment and transformation work has led to an almost complete set of stop locations and accompanying timetables, describing the offer on a typical weekday in 2014.18 The resulting data were stored in GTFS19 format.

For the purpose of spatial aggregation of the results, boundary datasets of NUTS regions were used, as well as grid-based datasets of territorial typologies such as the degree of urbanisation.

RAIL ACCESSIBILITY IN ABSOLUTE TERMS

TRAVEL TIME CONCEPTS

Using passenger rail timetables for a typical weekday, we have computed the travel time starting from every station in the EU, EFTA and UK to any other station to which services might be available, allowing for a travel time of less than 1.5 h. The result of such travel time calculation obviously depends on the requested time of departure. To evaluate the usefulness of services for daily travel, we have focused on services available during morning and evening peak hours. To capture differences in frequency we defined fixed preferred departure times from each station of origin. We searched for the best available connection to the destination for each of these departure times. In all, we ran the origin-destination calculations 18 times for each pair of stations, i.e. for preferred departures each quarter of an hour in two two-hour peak periods: one in the morning, another in the evening. This workflow has produced two results per origin/destination pair of stations. Figure 13 illustrates the origin/destination analysis process by means of a fictitious example during the morning peak period.

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17 Source: JRC, see: https://data.europa.eu/euodp/en/data/dataset/jrc-ghsl-ghs_pop_eurostat_europe_r2016a
18 More details on this preparatory work are provided in: Poelman and Ackermans (2016), pp. 13-14.
The first result is the **optimal effective travel time**. Amongst all reported connections between a pair of stations, this is the shortest travel time between the scheduled departure time of the first train of a trip and the scheduled arrival time of the same trip (in the example shown in Figure 13 this is the shortest red line, leaving at 08.40). For example, two stations might be linked by frequent but slow local trains, but also by few faster direct trains. In that case, the optimal effective travel time will measure the time between departure and arrival of the fast train, even if this kind of service is more the exception than the rule on that particular connection.

The second one is the **average total travel time**. The total travel time takes into account the initial waiting time before boarding the first available train (in Figure 13 this is the average time between all the dark green and light green dots). For each requested departure time, the trip planner searches for the best available connection. This is the one that ensures the earliest arrival time. If frequent and fast services are available, the average waiting time before boarding will be short. If only few services are available, or if most of the services are too slow to be useful for reaching a particular destination, the average of the initial boarding time can become much higher.
ASSESSING TRAVEL TIME BETWEEN STATIONS

In preparation of the travel time computations, we first needed to draw up a list of station pairs for which we would examine the travel times. The departure stations on that list are all stations in the EU or EFTA + UK. The destination stations are all stations that might possibly be reached within 1.5 h. As we wanted to assess accessibility within 1.5 h of travel time only, it was superfluous to consider all stations in Europe as destinations. Therefore, we have limited the list of destinations to stations within a certain geographical search radius around the departure station. At least all destinations that could possibly be reached within 1.5 h of optimal travel time should be located within this search radius. To define a suitable search radius for each of the departure stations, we used the results of an earlier analysis of travel times between cities. For each combination of departure and arrival cities, that analysis provided us with the minimum travel time and the straight-line distance covered. Taking into account only connections of maximum 1.5 h between cities, for each city we calculated the longest straight-line distance covered by any reported rail trip from or to that city. These distances were allocated to the city centroid points. From the city centroids we interpolated a 1 km² raster of modelled maximum distances, providing full coverage of the EU + EFTA + UK. The interpolated values were then allocated to the stations located in the raster cells. As a result, most of the stations now had an estimated maximum search radius, influenced by the optimal outreach of services available in the surrounding cities. For some stations, the interpolation led to missing values, especially when the station did not have enough cities in its neighbourhood. In these cases, we replaced the missing values with a default value of 200 km. The maximum distances by departure station allowed us to reduce the set of pairs of stations to only those for which the straight-line distance between origin and destination is not more than the maximum search distance. The final list of station pairs contained almost 19 million pairs to be examined.

For all selected pairs of stations, origin-destination calculations have been performed, searching for the optimal connection in terms of travel time. For each pair of stations, travel times needed to be examined eighteen times, using preferred starting times each quarter of an hour in a two-hour peak period in the morning and a two-hour peak period in the evening. The start and end times of these peak periods vary by country. For each country, we first counted the total number of departures by hour on an ordinary weekday. We selected the two-hour long periods in the morning and in the evening with the highest number of departures.

Consequently, a large number of origin-destination calculations needed to be run (more than 340 million calculations). This was made possible by using an optimised version of OpenTripPlanner Analyst. For each origin-destination calculation, this version reports the information required for further analysis and aggregation:

- the identifiers of the departure and arrival station
- the requested departure time (i.e. each quarter of an hour)
- the initial waiting time to the first boarding
- the total journey time (initial waiting time + trip time)
- the number of transfers, if any.

When a journey requires transfers between trains, a short transfer walk (maximum 900 m) is allowed if required. This situation can be required if two stations each serving a different part of the rail network are located very close to each other (for instance Paris Nord and Paris Est).

From the reported data for each origin-destination calculation, we can derive the effective travel time (total journey time minus initial waiting time).

The individual travel time results needed to be aggregated, first by pair of stations, and further by station of origin. The process followed was similar to the one used for the accessibility analysis between cities. For each pair of stations, we have calculated the minimum effective travel time (including transfer times if needed but excluding initial waiting) and the average total travel time (including initial waiting time and transfer times).

For further aggregation by departure point we have used two variants:

1. We only kept aggregates of pairs of stations where the minimum effective travel time does not exceed 1 hour and 30 minutes. This approach kept destinations for which the timetables show that it is technically feasible to reach them within 1.5 h at least once for departures during peak hours.
2. We only kept aggregates of pairs of stations where the average total travel time does not exceed 1 hour and 30 minutes. This selection of destinations is more realistic than the first one insofar as it takes into account the initial waiting time before first boarding.

COMPUTING THE ACCESSIBLE POPULATION

The origin-destination calculations provided results by pair of stations. We wanted to link all departure and arrival stations to the numbers of inhabitants living in the close neighbourhood of the stations, assuming they can reach the station within 15 minutes of walking. We first established the spatial relationship between the population distribution and the individual station locations. We took into account all populated grid cells located in a square neighbourhood of 3 x 3 cells around any departure or arrival station.

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21 Interpolation using inverse distance weighting with a variable radius, 12 sample points and exponent 2 of the distance.
24 This selection results in a list of almost 3.9 million station pairs.
To reduce the computational burden, we first constrained the EU-wide population grid to only those areas located nearby the stations. A simple point-to-raster operation on the set of railway stations provided us with a grid of cells in which at least one station is located. By expanding this grid by one cell, we obtained a grid of $3 \times 3$ km squares around all stations. This grid was used as a mask to filter the entire $1$ km$^2$ population grid, keeping only the population grid cells in the neighbourhood of the stations.

All selected population grid cells were converted into cell centroid points. Secondly, all station points were snapped to the nearest $1$ km$^2$ grid-cell centroid point. From the combination of these two point layers a distance matrix was created\textsuperscript{25}, containing all combinations of populated grid cells and their neighbouring stations (including the unique station identifier), provided that the distance between the population cell centroid and the station grid cell point is not more than the square root of $2$ (see Figure 14).

FIGURE 14: Grid cells and cell centroids in the neighbourhood of a station

\textsuperscript{25} We used the ‘generate near table’ tool in ArcGIS Desktop.
Next, two instances of the distance matrix table were joined to the table with the selected origin-destination data. One instance was joined to the departure stations and another to the arrival stations. This operation allowed the production of a table with all unique combinations of populated grid cells around departure stations and populated grid cells around the arrival stations.

Grouping this table by grid cell around every departure station we calculated the sum of accessible population, i.e. the population living in the grid cells close to all selected arrival stations. Figure 15 provides a simple illustration of this process, showing the case of a single departure station giving access to two destination stations. The population of the grid cells in the immediate neighbourhood of the two destination stations (i.e. the orange cells) is summed (avoiding double counting of grid cell population) and is allocated as accessible population to each of the cells around the departure station (i.e. the green cells).

**FIGURE 15:** Selection of cells neighbouring departure and arrival stations
The workflow produced two tables containing data per grid cell identifier, each containing the total number of accessible population within 1.5 h, one by using the optimal travel time, the other one using the average total travel time.

To compute the population accessible by means of a combination of rail travel and short bike trips, we followed a workflow similar to the one used for the combination of rail and walking. The only difference was the definition of the areas in the neighbourhood of the departure and arrival stations. As proxy of the areas easily accessible by bike around each of the stations we took into account all grid cells that have their centroid at less than 3.2 km from the centroid of the cell in which the station is located. We first created a raster of the Euclidian distance to the cells containing departure stations (where the search radius was set to maximum 4000 meters). This enabled a selection of all cell centroid points in the close environment of the departure stations. Only populated points within 3.2 km from station grid cell centroids were kept.

Finally, we computed three different combinations of rail travel and active modes, each using a specific combination of cells neighbouring the departure and arrival stations:

1. a short walk to the departure station, a train trip and another short walk to the final destination (Figure 16)
2. a short bike ride to the departure station, a train trip and a short walk to the final destination (Figure 17)
3. a short bike ride to the departure station a train trip and another short bike ride to the final destination (Figure 18).

FIGURE 16: Grid cells within walking distance from departure and arrival stations

![Figure 16](image)

FIGURE 17: Grid cells within cycling distance from the departure station and within walking distance from the arrival station

![Figure 17](image)
CREATING RAIL ACCESSIBILITY GRIDS

The tables at grid cell level were joined to the GEOSTAT grid cell centroid points and converted to grids according to the GEOSTAT 1 km² grid specification.

Grids cells outside the areas that are neighbouring the stations obtained ‘no data’ values. To enable further grid computations these ‘no data’ values were converted to 0. For that purpose, the ‘Is Null’ operation was used, producing a grid where ‘NoData’ cells have value 1 while the other cells have value 0. This grid was used as input for a conditional grid operation whereby cells of the IsNull grid, having value 0, obtained the accessibility value while the others were set to value 0.

Next the grids were filtered to retain only cells in which population is > 0 according to the GEOSTAT 2011 population grid. This was done using a Set Null operation whereby all values for which GEOSTAT population = 0 were converted to NoData.

BENCHMARKING ACCESSIBILITY: POPULATION IN A 120-KM RADIUS NEIGHBOURHOOD

For each grid cell with population > 0, we needed to determine the population living in a circular neighbourhood of 120-km radius. In principle this could be done by means of a simple raster operation (focal sum of population in a circular neighbourhood). For the purpose of our analysis, we wanted to avoid taking into account population in overseas areas, because we wanted to benchmark rail accessibility exclusively, without taking into account possible ferry connections. As the focal sum in a grid environment does not distinguish between neighbouring land areas and overseas areas, we needed an alternative solution for those areas located closer than 120 km from the coast.

First, we divided the GEOSTAT population point layer into two parts. The interior part contained all populated points located at minimum 125 km from any coast. For that purpose, we first selected the relevant coastlines, buffered these by 125 km and selected only the points falling outside the coastal buffer areas. For all ‘interior’ cells we obtained a grid of the population living in a circular 120-km radius neighbourhood using a simple focal sum grid operation.

For points located closer to the coast this raster approach could not be applied. We first created a land mass polygon layer in which each mainland territory, including possible islands connected by a bridge and/or tunnel constitute a unique polygon. Then, a Python script looped through all populated points located within the 125-km-wide coastal areas. This script first created a buffer of 120 km around the point. This buffer was intersected with the unique land mass layer. The resulting intersected buffers were dissolved on the GEOSTAT point identifier and were stored as single-part polygons. Next, only the buffer polygon containing the GEOSTAT point itself was selected. This excluded all overseas buffer parts that are not reachable via a fixed link. a search tolerance of 700 m was used in case a populated point falls just outside the coast. Finally, all GEOSTAT points inside the selected buffer area were taken into account. Their population was summed, allocated to the point around which the buffer was created and written to a table.

The resulting tables were all joined to the GEOSTAT grid cell centroid points and converted to a 1 km² raster.
CALCULATING TRANSPORT PERFORMANCE

In the previous steps we created grids of (absolute) accessibility and a grid of neighbouring population (in 120-km radius). All these grids have data for cells that have a GEOSTAT population > 0 and contain numbers of inhabitants that can be reached within 1.5 h or that live within the 120-km-radius neighbourhood. Hence, the creation of grids of transport performance was straightforward.

Each of the grids of absolute accessibility was divided by the grid of population in a 120-km-radius neighbourhood and multiplied by 100. Finally, the data from the resulting grids were also transferred to the GEOSTAT grid cell centroid points. This facilitated tabular aggregations of the indicators.

AGGREGATING GRID DATA TO REGIONAL OR TERRITORIAL LEVELS

To compute aggregated values of grid-level accessibility and transport performance metrics at the level of NUTS regions or of any other territorial classification, we needed to take into account the population distribution inside the regions or territories. Hence, all aggregates are population-weighted averages of the grid-level data.

We have stored all grid values in a table related to the grid cell centroid points. In this table we also registered the identifiers of the regions or territories for which we wanted to compute aggregates (e.g. NUTS codes, degree of urbanisation codes, codes of urban centres, etc.). Hence, all aggregates could easily be computed using that table by first multiplying the accessibility metrics with the grid cell population, summing these multiplications by region or territory, and finally dividing by the regional sum of the grid cell population.

ANNEX 2 - A REFINED CLASSIFICATION WITHIN THE DEGREE OF URBANISATION TYPOLOGY

Within the framework of the degree of urbanisation typology, a refined typology has been created, adding an additional level of classification at grid cell level. This second level contains six classes:

- **Cities**: this is the original degree of urbanisation class, i.e. settlements of at least 50,000 inhabitants in a high-density cluster of grid cells (> 1,500 inh./km²).
- **Towns**: these can be dense towns, with a density of more than 1,500 inh./km² and a population between 5,000 and 50,000, or semi-dense towns within the same range of population size, but with a density between 300 and 1,500 inh./km², provided they are located at more than 2 km from cities or from dense towns.
- **Suburbs**: these are cells belonging to urban clusters (i.e. clusters of cells with a density of at least 300 inh./km² and a total cluster population of at least 5,000 inhabitants) that are not part of cities or towns.
- **Villages**: settlements with a population between 500 and 5,000 inhabitants and a density of at least 300 inh./km².
- **Dispersed rural areas**: rural grid cells with a density between 50 and 300 inh./km².
- **Mostly uninhabited areas**: rural grid cells with a density between 0 and 50 inh./km².
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DATA

Aggregated indicators by region and by type of territory, as well as the grid datasets of accessibility, proximity and transport performance, are provided in separate data packages.
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