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HOW MANY PEOPLE CAN YOU REACH BY PUBLIC TRANSPORT, BICYCLE OR ON FOOT IN EUROPEAN CITIES?

Measuring urban accessibility for low-carbon modes

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Working Papers

A series of short papers on regional research and indicators produced by the Directorate-General for Regional and Urban Policy

WP 01/2020

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Luxembourg: Publications Office of the European Union, 2020

PDF ISBN 978-92-76-10253-3 doi:10.2776/021137 KN-02-20-050-EN-N

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EXECUTIVE SUMMARY

Good urban public transport can reduce congestion, air pollution and greenhouse gas emissions. It can improve a city's quality of life and strengthen its economy. This working paper measures access to public transport for many European cities using the United Nations Sustainable Development Goal indicator. It shows that in virtually all cities at least 80% of the population has easy access to public transport. In addition, it reveals that 56% of an average city's population has access to at least 10 departures an hour. Access to high-frequency departures is highest in cities with at least 1 million inhabitants and considerably lower in cities with fewer than 250 000 inhabitants, although some cities perform much better or worse than their size implies. A comparison between the population accessible by public transport with the nearby population in 42 cities shows that within 30 minutes people can only reach 24% of the population living within a distance of 7.5 kilometres. Walking and cycling perform well in cities with dense road networks, higher densities and fewer steep slopes. Finally, the paper provides a set of context indicators to help to interpret the results, including the speed of public transport, vehicle kilometres travelled, building block size and density. To provide easy access to all this information, the working paper is accompanied by city fact sheets which report its various indicators and benchmark them to other cities.

INTRODUCTION

Cities can offer excellent accessibility by walking, cycling and public transport. Making these mobility modes attractive can improve the quality of life in cities and reduce greenhouse gas emissions. The United Nations Sustainable Development Goals (SDGs) recognise this and include indicators evaluating convenient access to urban public transport.

This paper starts by assessing who has convenient access to a public transport stop. This is the core SDG indicator (11.2.1) on urban public transport. Next we will evaluate to how many departures people have access within walking distance. Using the urban accessibility framework developed by the European Commission (EC), Organisation for Economic Co-operation and Development (OECD) and the International Transport Forum (ITF)¹, it then measures how many people can be reached using public transport in a more limited set of cities and assesses how that compares to the population living nearby. These metrics will be contextualised by comparing them with the spatial distribution of population and the performance of the street network in providing accessibility by means of walking or cycling in all cities.

To ensure a high level of comparability, we use the EU-OECD Functional Urban Area definition for urban centres². In addition, we use high-resolution geospatial data on population (and employment) distribution. In this way, we can capture the spatial heterogeneity of the cities³ and explore diversity within them. Maximum compatibility with the UN methodology for the SDG indicators has been ensured.

Measuring the indicators within this framework relies on three key features: 1) complete and reliable data on public transport timetables; 2) detailed data on the spatial distribution of population in cities; and 3) a complete street network and related characteristics. The computation of these indicators is quite demanding. We have calculated these indicators using cloud computing. However, a single city can be calculated using a (powerful) desktop computer. Although we do not have public transport data for all European cities, the availability of this data has increased substantially in recent years. With annually updated, comprehensive public transport data, these indicators could be used to monitor progress over time. Up-to-date street network data are available from commercial providers and open sources, such as Open Street Map⁴. Annually updated population grids will become available for Europe from 2024.

¹ ITF (2019).

² Dijkstra, Poelman and Veneri (2019).

³ In this paper, we use the term city as a synonym of urban centre; city does not refer to the local units with the majority of their population in an urban centre, which is the definition of a city in the Functional Urban Area and the Degree of Urbanisation. See European Commission (2019) for more details on these territorial concepts.

⁴ <https://www.openstreetmap.org>

1. ASSESSING ACCESS TO PUBLIC TRANSPORT

1.1 WHO HAS EASY ACCESS TO A PUBLIC TRANSPORT STOP?

An earlier working paper⁵ presented a method to measure access to public transport services. It takes into account where people live and what level of services they can easily access. Since the drafting of the earlier paper, the UN member states have adopted the 2030 Agenda for Sustainable Development, which includes 17 SDGs. Under SDG 11⁶, one of the targets is to provide access to safe, affordable, accessible and sustainable transport systems for all, improve road safety, notably by expanding public transport, paying special attention to the needs of those in vulnerable situations, women, children, people with disabilities and older people. Progress towards this target is measured by indicator 11.2.1: the proportion of population that has convenient access to public transport, by sex, age and people with disabilities. UN-HABITAT, the UN agency responsible for indicator 11.2.1, has developed a methodology for producing the indicator. To contribute to UN efforts towards SDG indicator collection, we have aligned our methodology to that developed by UN-HABITAT⁷.

The core SDG indicator measures which part of the population has easy access to a public transport stop, regardless of the transport mode (in particular, bus, tram, metro, train) or the frequency of the provision available at that stop. The assumption is that people are willing to walk 500 metres to reach a public transport stop. The walking distances are measured along the street network, which means that the density of the street network and obstacles such as waterways, motorways or railways are taken into account. The share of population with access to a public transport stop within 500 metres' walking distance is then calculated at the level of each urban centre. An urban centre is a cluster of contiguous 1 km² grid cells with a density of at least 1 500 inhabitants/km² and a total population of at least 50 000⁸. Using a grid-based city concept independent from administrative borders greatly enhances the comparability of the results. Map 1 shows the results for 685 urban centres in EU-27, EFTA countries and the United Kingdom⁹.

Access to a public transport stop within walking distance is usually not problematic for a vast majority of urban centre populations in European countries. In more than 45% of the cities reviewed, the share of population with access to a nearby stop exceeds 95%. Only 22 of the 685 cities provide such access to fewer than 80% of their population. Most of the cities with low values are smaller Dutch cities, where a large share of trips within the city is typically done by bicycle.

Country averages of the share of urban centre population with easy access to stops range from 87% in Romania to 97% in Spain, Greece, Austria, Malta and Luxembourg. Among the cities under review, the population size of the city barely influences the value of the SDG indicator: for cities with fewer than 100 000 inhabitants it averages at 93%, whereas in cities with more than 2 million people the average is 96%.

Although SDG 11.2 also focuses on particular population categories, computing specific indicators on convenient access would require high-resolution intra-urban data on specific population categories. Furthermore, additional data on appropriate infrastructure designed to meet the needs of people with disabilities should be considered. Currently, this kind of data is difficult to find or to harmonise and analyse for many European countries and cities. For that reason, we will not develop this aspect further in this paper. Modelling the sub-local distribution of population categories by combining official input data with disaggregation processes is useful for developing indicators on specific population groups¹⁰. The European population grid for 2021 will provide a breakdown by age, sex and country of birth, enabling us to calculate which group has better or worse access to public transport.

⁵ Poelman and Dijkstra (2015).

⁶ SDG 11: Make cities and human settlements inclusive, safe, resilient and sustainable.

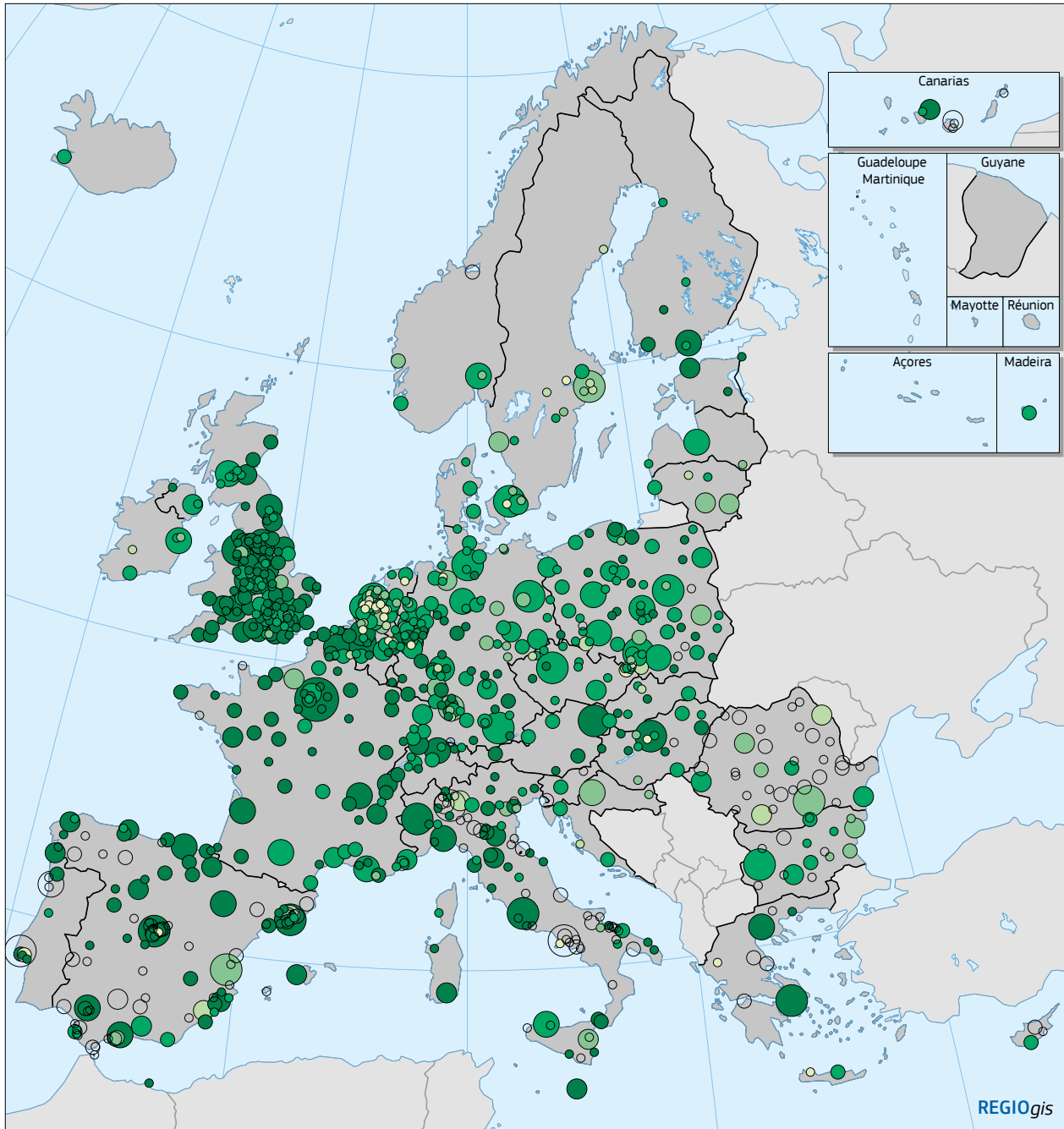
⁷ UN-HABITAT (2018).

⁸ European Commission (2019), p. 31.

⁹ The EU-27, UK and EFTA countries include a total of 837 urban centres defined on the basis of the 2011 population grid.

¹⁰ For instance, a high-resolution mapping of migrants, in: Alessandrini et al. (2017) has been used to assess proximity to urban public transport for migrant populations; see Tintori et al. (2018).

MAP 1: Population with a public transport stop within 500 metres' walking distance



Population with a public transport stop within 500 m walking

- | % of total population | Urban centre population |
|-----------------------|-------------------------|
| ○ < 80 | ○ < 100000 |
| ○ 80 - 85 | ○ 100000 - 250000 |
| ○ 85 - 90 | ○ 250000 - 500000 |
| ○ 90 - 95 | ○ 500000 - 1000000 |
| ● ≥ 95 | ○ 1000000 - 5000000 |
| ○ No data | ○ ≥ 5000000 |

UN SDG indicator 11.2.1
 Sources: public transport operators, UIC, Eurostat, NSIs,
 Copernicus Urban Atlas, TomTom, OpenStreetMap, REGIO-GIS



1.2 WHO HAS EASY ACCESS TO FREQUENT PUBLIC TRANSPORT?

Although being able to easily access a public transport stop is an important first step, the quality and frequency of the provision can be quite varied. For that reason, we developed additional indicators to take into account the transport mode and frequency of the services available at each of the stops.

On average, the metro and trains provide faster and more frequent services than buses and trams. Therefore, we distinguished two groups of transport modes: (1) bus and tram; and (2) metro and train. To reach a bus or tram stop we assumed people would be willing to walk 500 metres. To get to a train or metro station, we assumed people would be willing to walk somewhat further, i.e. 1 km. To assess the frequency of the departures we selected an ordinary weekday. For each stop in the urban centre, we counted the number of departures between 6:00 and 20:00. By combining the departure counts per stop with the data on the number of people living nearby, we obtained a number of accessible departures for each inhabited place in the city. Furthermore, from the hourly average number of departures, we created a typology of five access classes, based on proximity and departure frequency. This typology is illustrated in figure 1.

In this typology, very high access requires the availability of metro and /or train services, while a high level of access can also be reached without metro or train, providing that bus and/or tram services run at high frequency.

This analysis requires the availability of comprehensive machine-readable timetable data for all public transport in the cities. We were able to retrieve and analyse data for 461 urban centres, i.e. 55% of the number of urban centres in the EU + EFTA and 69% of their populations.

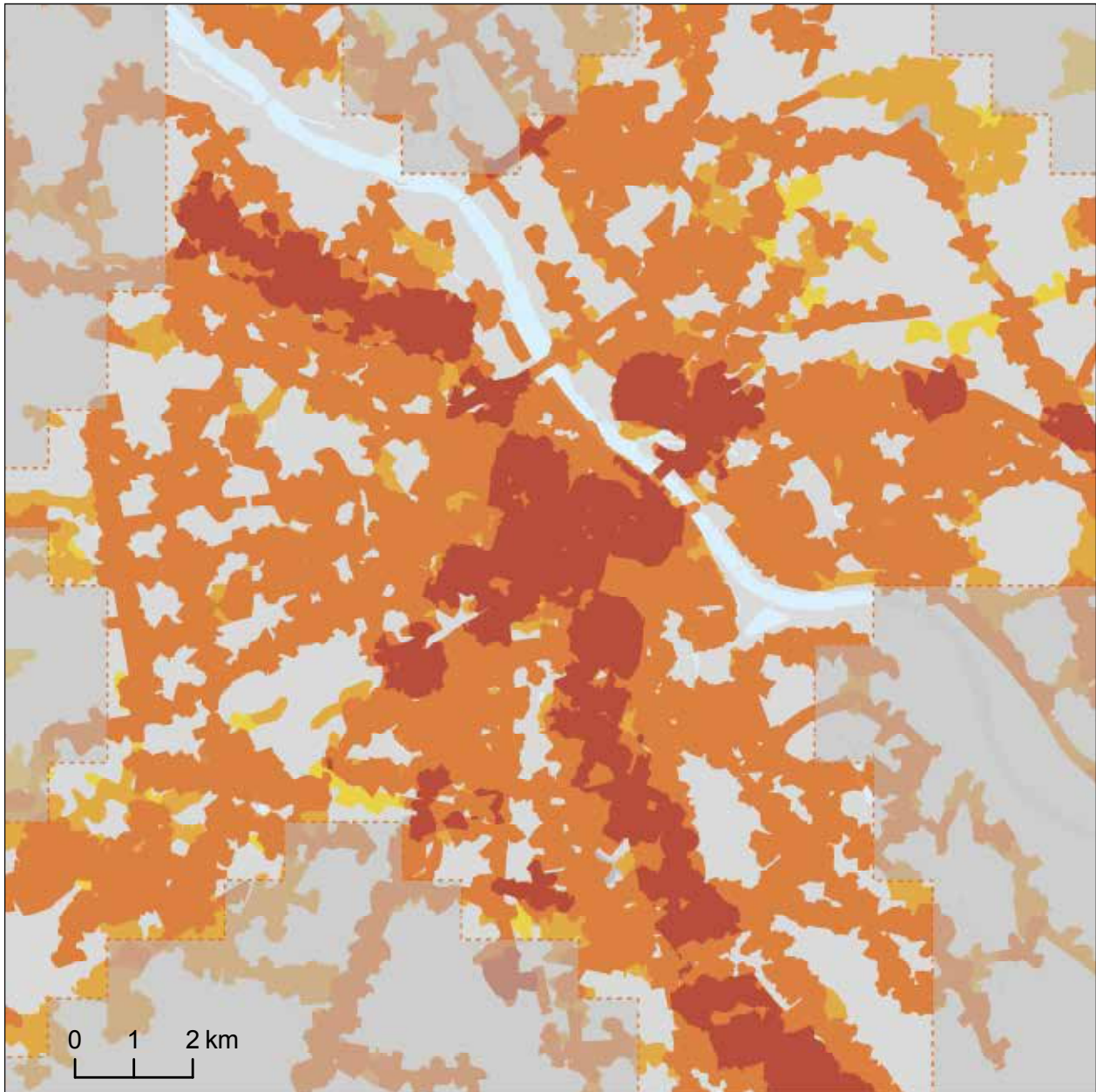
The results of this analysis can be presented in various ways. Detailed maps (such as map 2) provide insight in the geography of access and frequency typology inside the cities¹¹.

FIGURE 1: Typology of public transport service frequencies

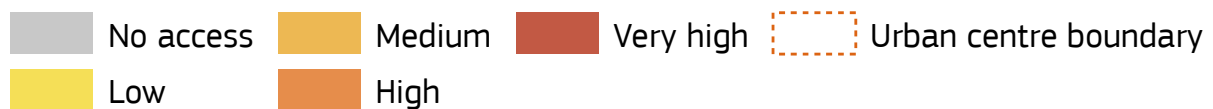
		Metro and train (within 1 km walking)				
		Frequency per hour	High (> 10)	Medium (4 to 10)	Low (< 4)	No services
Bus and tram (within 500 metres' walking)	High (> 10)	Very high	High	High	High	
	Medium (4 to 10)	High	Medium	Medium	Medium	
	Low (< 4)	High	Medium	Low	Low	
	No services	High	Medium	Low	No access	

¹¹ The interactive map viewer enables an in-depth exploration of the detailed results for all available cities: https://ec.europa.eu/regional_policy/mapapps/public_transport/sdg-city-accessibility.html

MAP 2: Warsaw: typology of public transport frequencies



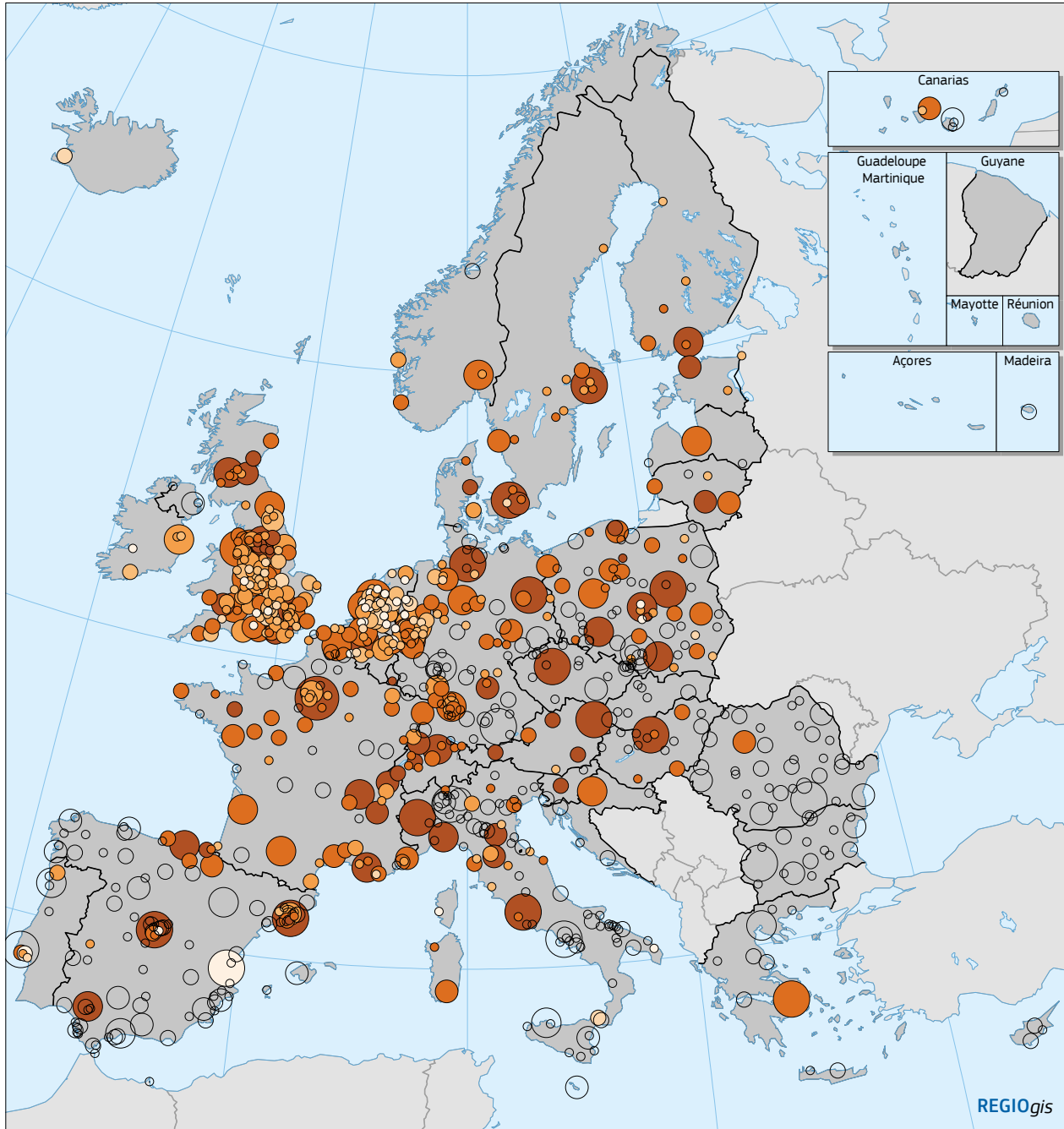
Typology of public transport frequencies



To compare cities, more aggregated indicators are needed. Therefore, we computed the median number of departures available within walking distance (map 3). This means that in a city, half of the population has access to at least this number of departures an hour. In some cities – for instance, Vienna, Madrid, Warsaw, Copenhagen and Barcelona – half of the population has access to at least 50 departures an hour during weekday daytime hours. In cities with more than 2.5 million

inhabitants, the median number of departures varies between moderate values in Germany's Ruhr area (11.7 departures) and in Athens (18 departures) and high figures in Berlin (43) and Madrid (64). The median number of departures tends to be somewhat lower in smaller cities, although in each size category of cities we found a wide diversity in the median number of departures.

MAP 3: Public transport departures available within walking distance



Public transport departures in urban centres, 2018

Number of departures	Urban centre population
○ < 4	○ < 100000
○ 4 - 6	○ 100000 - 250000
○ 6 - 8	○ 250000 - 500000
○ 8 - 12	○ 500000 - 1000000
○ 12 - 24	○ 1000000 - 5000000
○ >= 24	○ >= 5000000
○ No data	

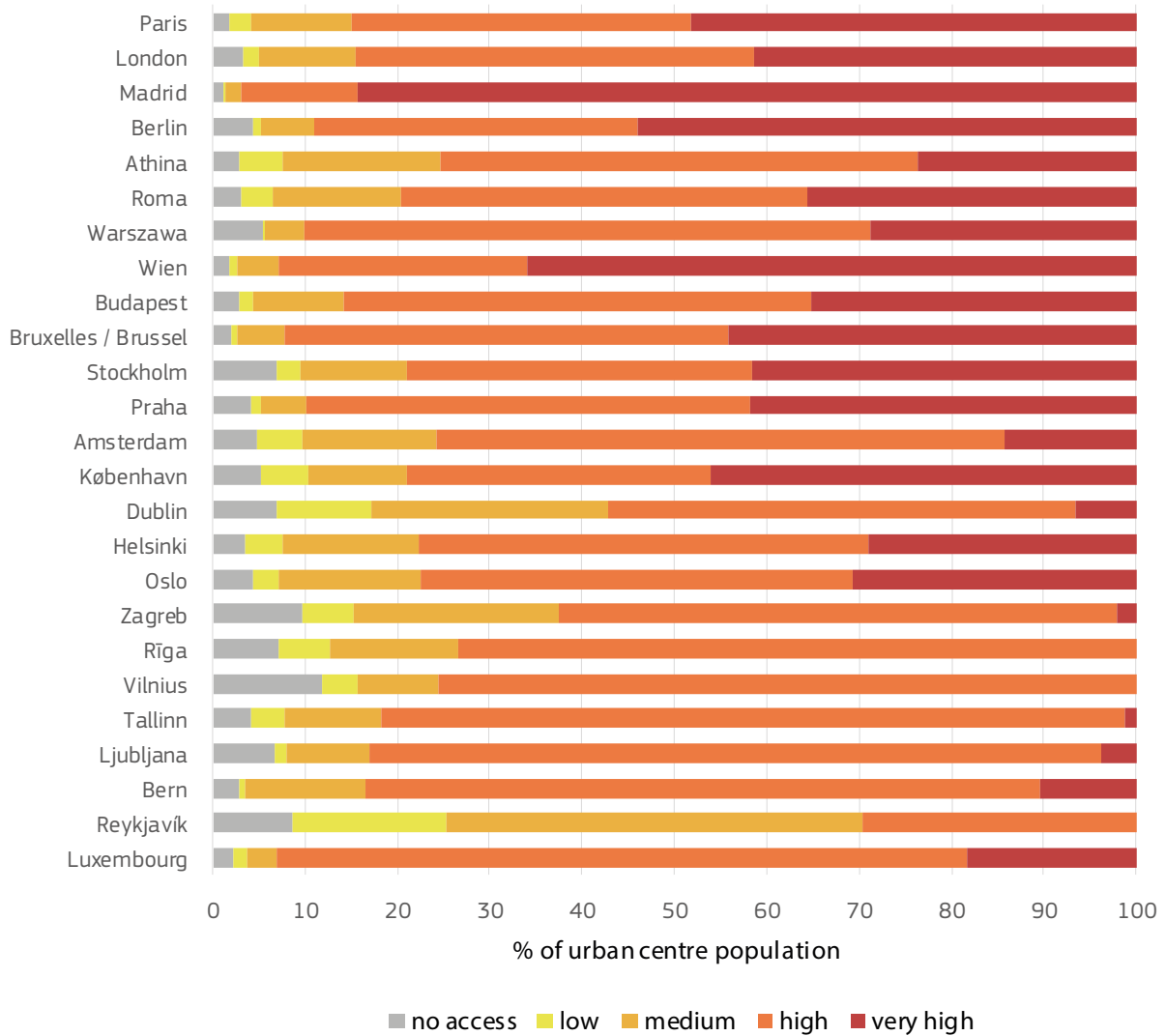
Population-weighted median number of hourly departures between 6:00 and 20:00 available within walking distance (500 m to bus/tram stop; 1 km to metro/train).
Sources: public transport operators, Eurostat, REGIO-GIS



Another way of summarising a city’s situation is to split the population according to the level of access. Figure 2 illustrates this distribution in capital cities. In capitals like Madrid, Brussels, Vienna and Luxembourg, more than 90% of the population can access high to very high service frequencies within walking

distance. The highest category of this typology is mainly present in larger cities where metro networks operate. The availability of nearby highly frequent services is much lower in cities such as Dublin, Zagreb or Reykjavik.

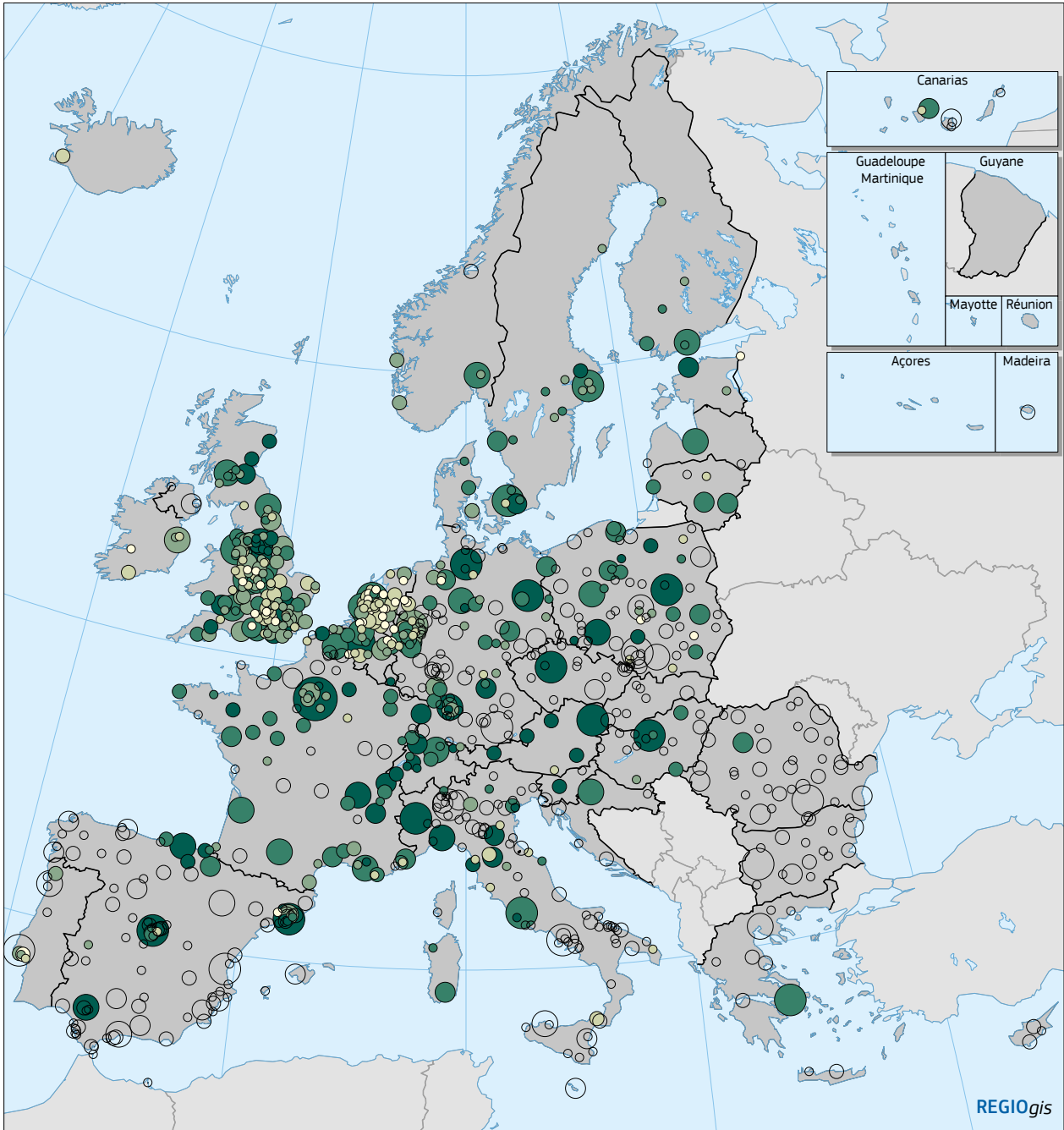
FIGURE 2: Population of capital cities by public transport frequency typology, ordered by population size



Map 4 shows the share of population with access to services of high or very high frequency for all cities where data are available. On average, cities provide high-frequency access to 56% of their population. In cities with more than 1 million inhabitants, the average share is 82%. In cities with fewer than 250000 inhabitants, the average share is 51%, although even in that size category there are cities with shares above 90%

(for instance, in Vitoria-Gasteiz, Luxembourg, Grudziądz, Innsbruck, Rennes and Dundee). Relatively low shares are found in many – mainly smaller – cities in the Netherlands and UK although in the latter even some of the larger cities reveal shares below 65% (Birmingham with 63% and Greater Manchester with 61.4%).

MAP 4: Share of population with high or very high frequency of departures within walking distance



Population with (very) high level of access to public transport departures in urban centres, 2018

% of population	Urban centre population
○ < 20	○ < 100000
○ 20 - 40	○ 100000 - 250000
○ 40 - 60	○ 250000 - 500000
○ 60 - 80	○ 500000 - 1000000
○ >= 80	○ 1000000 - 5000000
○ No data	○ >= 5000000

Public transport stops with at least 10 departures an hour within walking distance (500 m to bus/tram stop; 1 km to metro/train)
Sources: public transport operators, REGIO-GIS

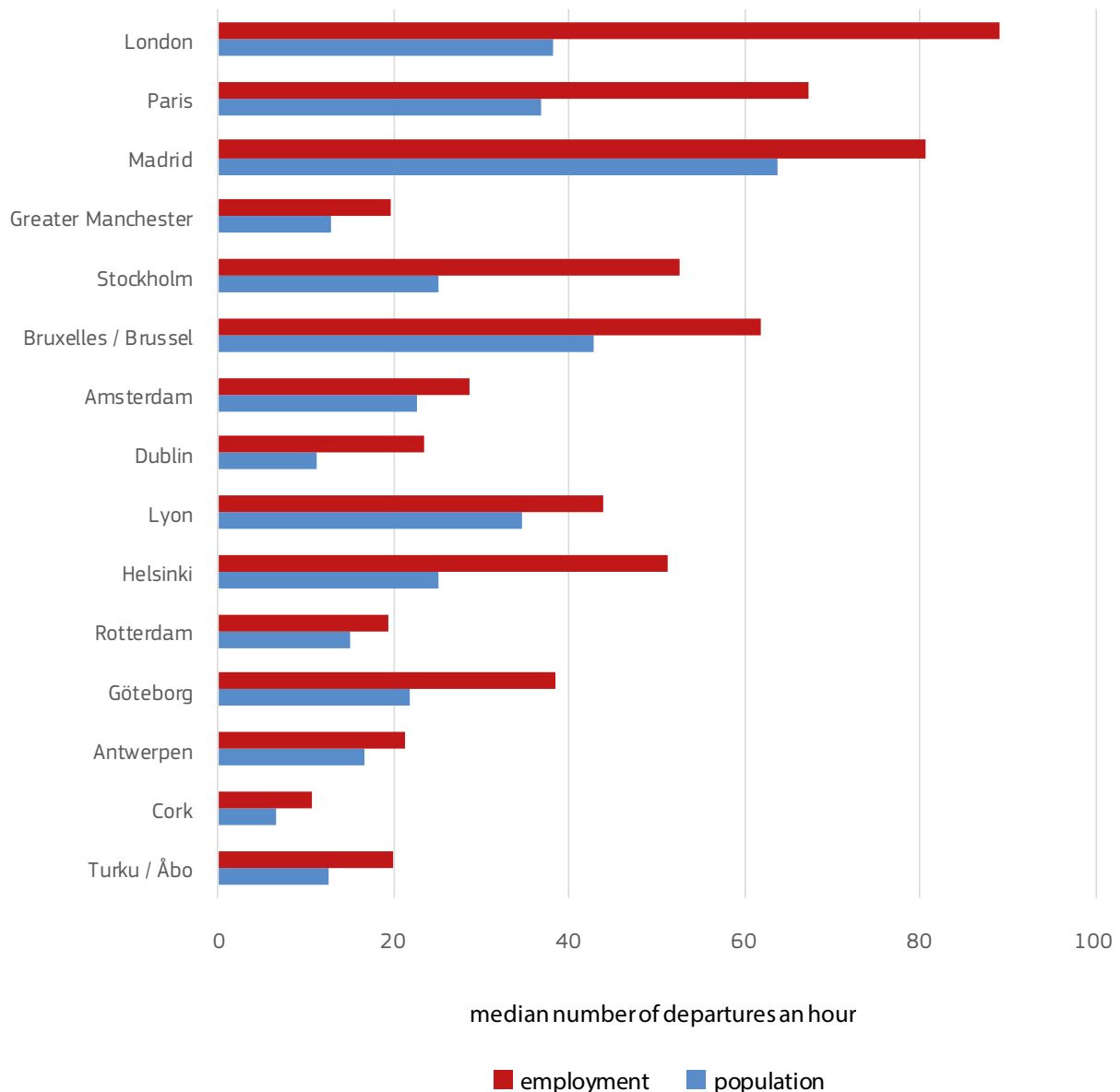


All the indicators we have discussed take into account the spatial distribution of the residential population (night-time population) within the city. The availability of urban public transport should also be assessed by taking into consideration where people work or spend their day. Unfortunately, data on the spatial distribution of employment are not as widely available as data on residential population. Estimates of daytime population are even harder to access¹².

In many cities with workplace-based employment, people at work have access to more departures than people at home. This is because in many cities employment is clustered around public transport nodes, such as train and metro stations.

Figure 3 shows the median number of departures an hour within walking distance of residential population and employment in a few capital and other major cities. High values related to employment (such as in London, Paris, Madrid and Brussels) indicate a high concentration of workplaces within walking distance of stops and stations with very frequent services. A comparison of people at home to those at work shows that in general more people at work have access to high-frequency services than people at home (figure 4)¹³.

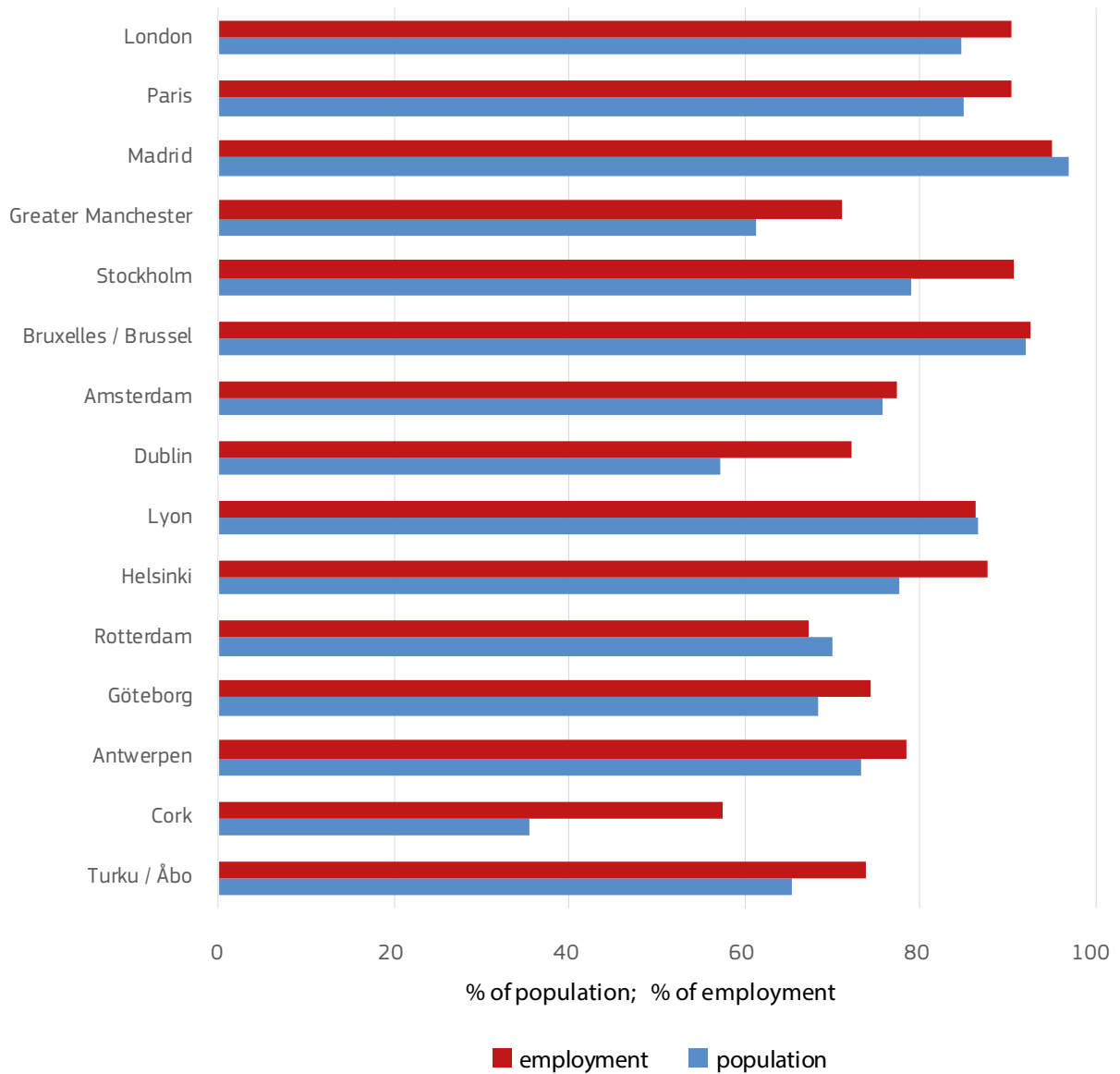
FIGURE 3: Median number of departures within walking distance of population and employment



¹² The methodological section of this paper discusses in more detail the availability and allocation of employment and daytime population data to Urban Atlas polygons.

¹³ Employment-related data on departure frequencies are available for over 200 cities. Detailed results can be consulted in a data file that can be accessed via: https://ec.europa.eu/regional_policy/en/information/maps/low-carbon-urban-accessibility.

FIGURE 4: Population and people employed having easy access to a high or very high frequency of departures



Despite the incomplete coverage of employment data, the differences shown in this analysis indicate the relevance of this data when assessing public transport. Apart from travel-to-work patterns, mobility must also cover access to a variety of daytime activities (such as education, leisure, shopping or administration). Hence, analysing the availability of public transport services in relation to the location of the daytime population is relevant. This is possible for three cities in Ireland and for Tallinn (Estonia). Figures 5 and 6 compare the metrics

for night-time and daytime populations and workplace-based employment¹⁴. In these four cities, people at work have access to the highest number of departures and more have access to high-frequency departures, whilst the residential population has access to the lowest number of departures and fewer people can access high-frequency departures. In Tallinn, however, the results for the night-time and daytime populations are quite similar.

FIGURE 5: Median number of departures within walking distance of night-time population, daytime population and workplace-based employment

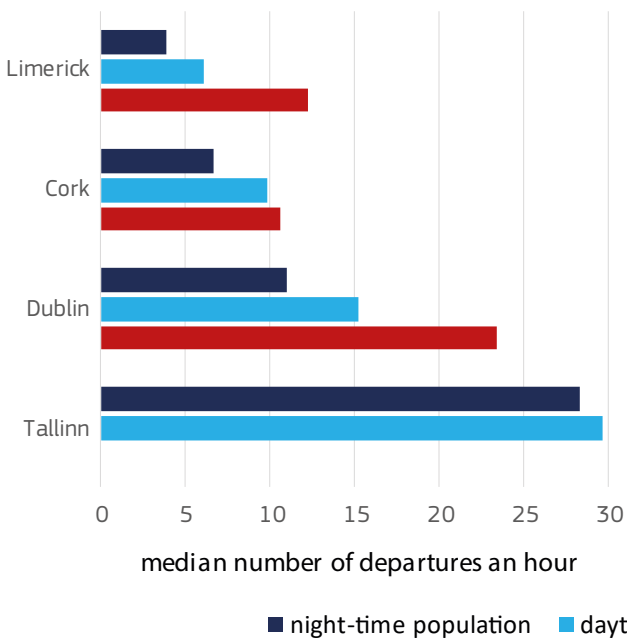
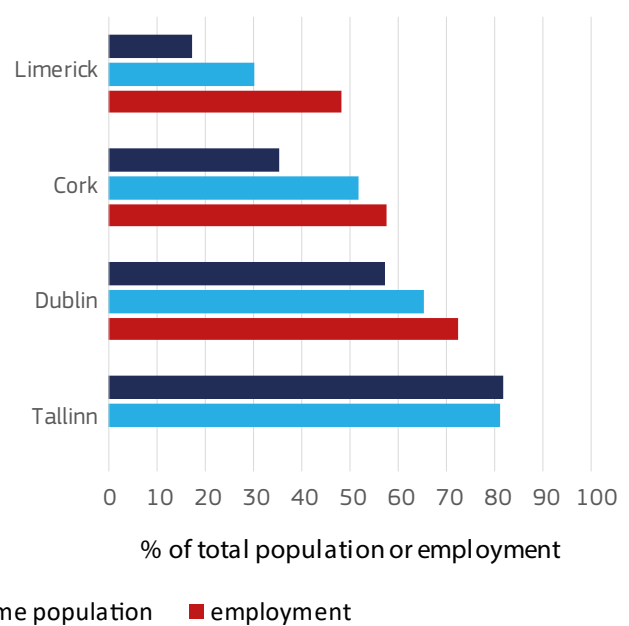


FIGURE 6: Night-time population, daytime population and people employed with easy access to a high or very high frequency of departures



¹⁴ Specific workplace-based employment figures for Tallinn are not available.

2. ASSESSING ACCESSIBILITY, PROXIMITY AND PERFORMANCE

2.1 ACCESSIBILITY: HOW MANY PEOPLE CAN EASILY BE REACHED USING PUBLIC TRANSPORT?

Access to a public transport system with conveniently located stops and frequent departures can promote sustainable mobility in cities. The indicators presented above, however, only indicate if it is easy to get on to public transport – they do not show what can be reached by public transport.

To assess what can be reached by public transport within a city, we first measured the travel time between all origins and destinations inside the urban centre. We used residential population as a proxy for the level of interest of a particular destination. Obviously, other factors could be taken into account, such as the presence of (public) services, employment or daytime population. Unfortunately, we do not have good data on services. Collecting data on services faces many obstacles, including a lack of harmonised definitions and a lack of data with a high spatial resolution. We were only able to assess accessibility to employment or daytime population for a limited number of urban centres.

We define the absolute level of accessibility as the number of people who can be reached within a fixed maximum time (for instance, 30 or 45 minutes), provided that the destinations are within the boundaries of the urban centre. In the transportation literature, this is called a cumulative opportunity index. The origins and destinations are the (inhabited) building blocks in the urban centre. Each block has an estimated population for 2011. The travel time we computed considers the scheduled timetables of all public transport in the city, waiting times and transfer times, and the walking time from the point of departure to the public transport stop and from another stop to the destination.

To calculate accessibility requires not only comprehensive timetables but also massive amounts of computing time. For that reason, we limited our calculations to a group of 42 cities, among which were many capital cities. Below, we will discuss the indicators resulting from this analysis. Detailed results are available in a set of fact sheets per city¹⁵.

2.2 PERFORMANCE AND PROXIMITY: DOES PUBLIC TRANSPORT PROVIDE EASY ACCESS TO THE NEARBY POPULATION?

For each origin within the city, we calculated the number of inhabitants who can be reached within a defined maximum time. Obviously, these figures do not only depict the suitability of the network or the performance of the public transport system, but also the spatial distribution of the population within a city and the city's size¹⁶.

Therefore, we compared accessible population with the nearby population. For each place of departure, we calculated the number of inhabitants living within a maximum straight-line distance around the departure area. The maximum distance defining that neighbourhood was chosen in relation to the transport mode with which we wanted to compare it. For public transport and cycling, we used a radius corresponding to a straight-line speed of 15 km/h, while for walking we assumed a speed of 5 km/h¹⁷. High values of nearby population indicate a high population density and a potential advantage in providing efficient transport services.

Transport performance is the ratio between the number of inhabitants accessible within the maximum travel time and the number of people living near to the place of departure. For easier reading, this ratio was multiplied by 100. The ratio indicates how well the transport mode performs in providing access to the nearby population.

Among the cities analysed, the public transport performance for trips within 30 minutes is a modest average of 24. This means that by using public transport, within 30 minutes a city resident can reach 24% of the population living within 7.5 km. City values vary significantly between 12 (Greater Manchester) and 48 (Luxembourg).

In all the cities analysed, public transport performs much better for journeys of up to 45 minutes, when the average becomes 57, with a minimum of 31 in Athens and a maximum of 97 in Kaunas (Lithuania) (figure 7). For a large city, a 45-minute journey and a distance of 11.25 km can be realistic for a trip. In smaller cities, however, people may rarely travel for 45 minutes and all destinations may be within less than 11.25 km. For example, the area of the Kaunas urban centre is quite small, just 56 square km. As a result, most people in that urban centre live less than 10 km from one another, thus the 11.25 km distance is never used.

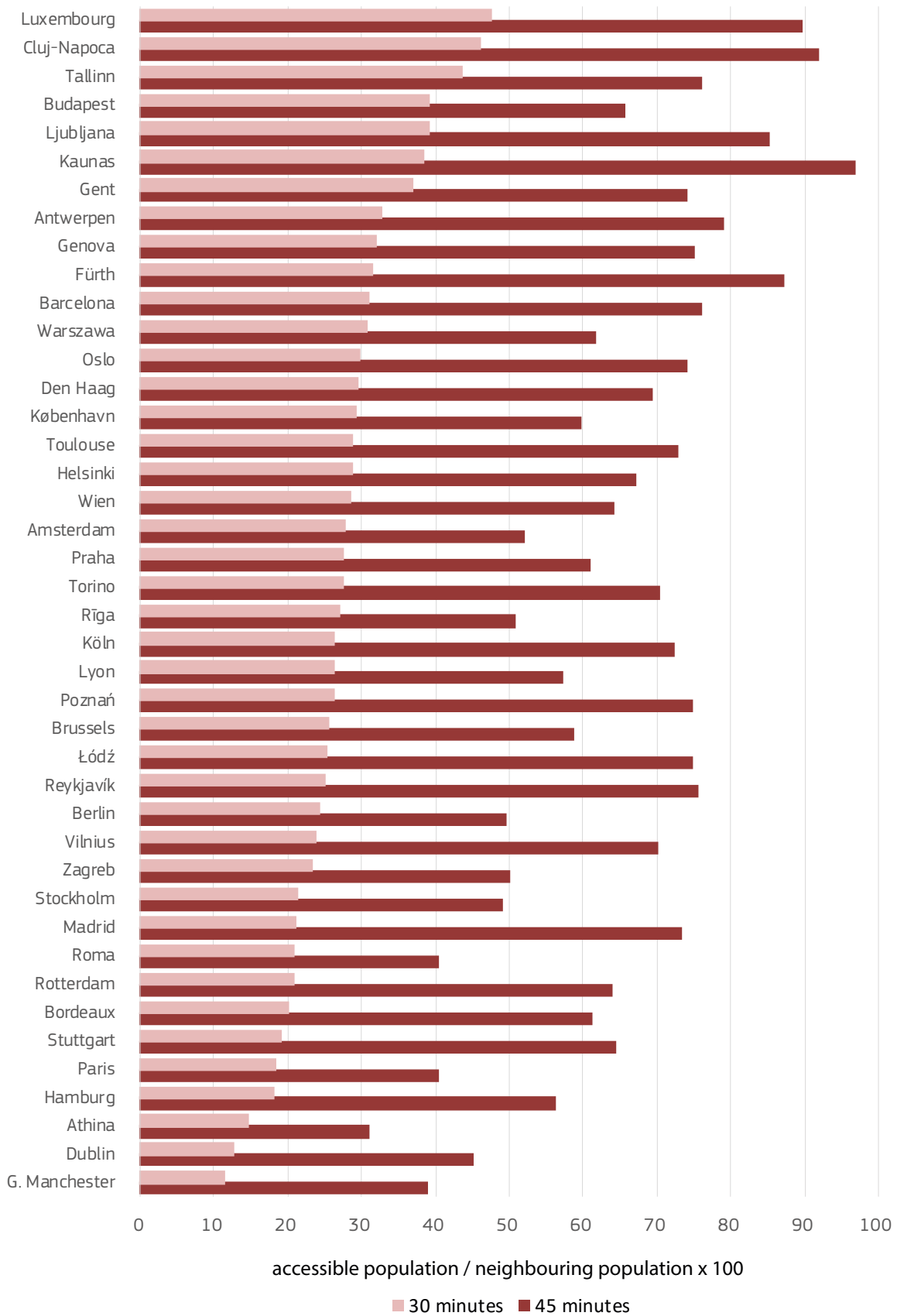
For 10 cities, we calculated access to employment by public transport. Usually, public transport performance for trips to workplaces is higher than to the residential population. In other words, public transport is more efficient in bringing people to places of employment than to (other) residential areas. A higher concentration of employment inside the city could also account for the difference between the two metrics. For instance, performance for trips within 45 minutes to workplaces reaches 82 in Madrid where trips of the same duration to night-time

¹⁵ See: https://ec.europa.eu/regional_policy/en/information/maps/low-carbon-urban-accessibility

¹⁶ For an in-depth discussion on the challenges regarding accessibility indicators, see ITF (2019), p. 13.

¹⁷ This means a radius of 2.5 km as the benchmark for 30 minutes' walking, 3.75 km for a quarter of an hour of cycling, 7.5 km for half an hour on public transport or cycling, and 11.25 km for 45 minutes on public transport.

FIGURE 7: Public transport performance within 30 and 45 minutes



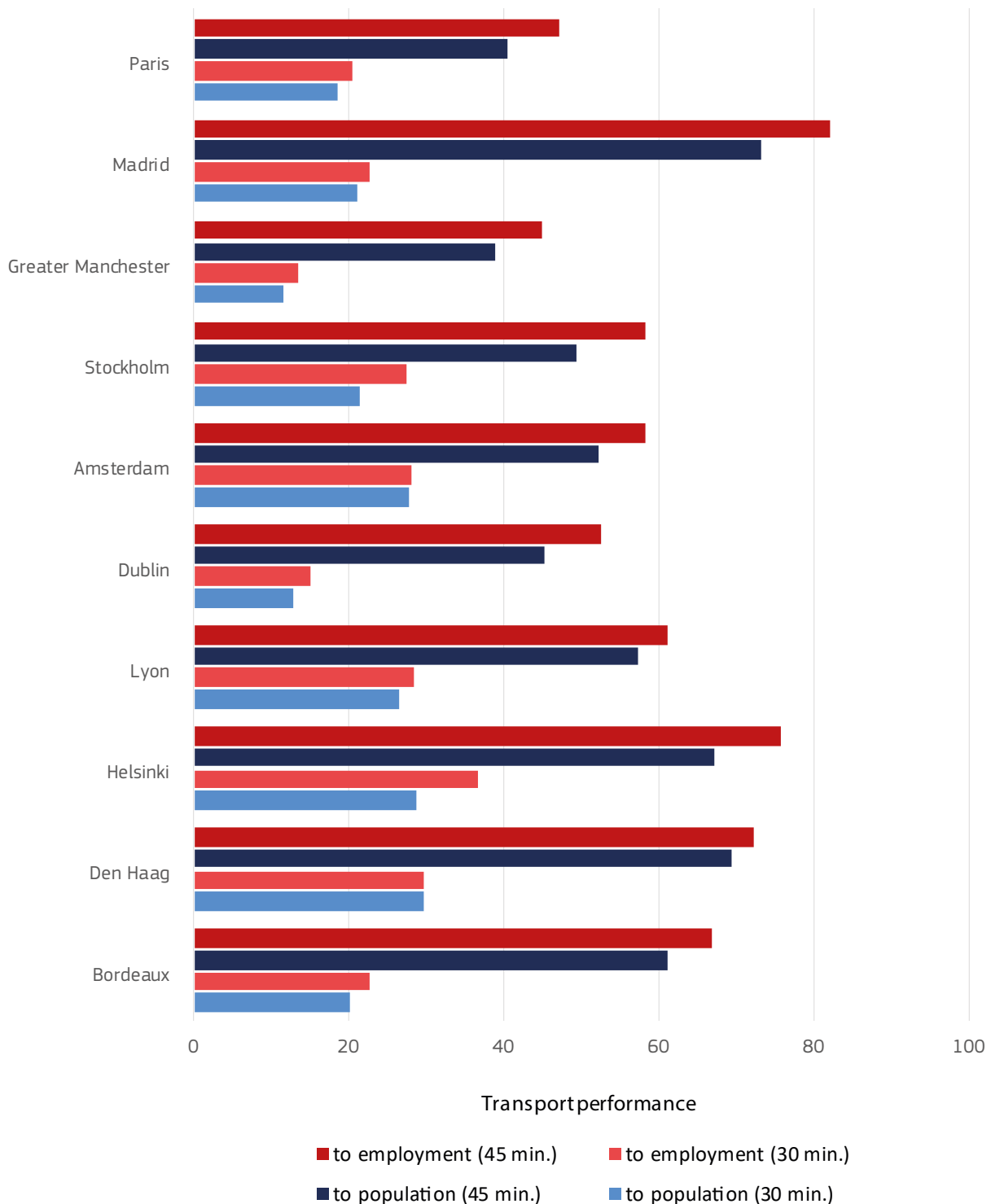
population achieve a value of 73. Figure 8 illustrates public transport performance in providing access to the residential population and employment within 30 or 45 minutes.

The performance is influenced by various factors, such as the frequency of the services, integration of the schedules for the different routes and the length of transfer times. Furthermore, the proximity of the stops to the places of origin and destination influences the walking times required in

combination with public transport. Finally, the actual speed of the vehicles – dependent on the road layout, congestion and appropriate infrastructure – also plays a role.

Using data on scheduled timetables means it is hard to assess how realistically the transport services actually follow the schedules. In principle, the scheduled timetables are expected to take into account any structural obstacles inhibiting the free flow of the vehicles.

FIGURE 8: Public transport performance relative to population and employment, for trips within 30 or 45 minutes



3. ACTIVE MOBILITY MODES (WALKING AND CYCLING): ACCESSIBILITY AND PERFORMANCE

Facilitating sustainable urban mobility goes beyond the provision of efficient public transport services. Active and clean mobility modes, i.e. walking and cycling, are well suited for short-distance trips within cities. Fostering walking and cycling can also help to reduce urban traffic congestion¹⁸. Using the same kind of indicator framework as for public transport, we assessed accessibility and transport performance by means of walking or cycling. To be able to compare the results with the public transport performance metrics, we analysed the same set of 42 cities.

For (very) short trips within cities, walking may often be the easiest way to move around. We calculated the population who could be reached during a walk lasting a maximum of 30 minutes and compared this with the neighbouring population living within a 2.5 km radius. The resulting transport performance by walking (figure 9) is influenced by the density of the street network and by possible obstacles to be circumvented (e.g. roads not accessible to pedestrians, railways, waterways). The average performance for walks within 30 minutes is 52, varying between 43 in Dublin and 61 in Tallinn.

Somewhat longer distances are often dealt with more efficiently by cycling. To ensure the maximum comparability with public transport analysis, we calculated the population accessible within a 30-minute bike ride. The related cycling transport efficiency compares this accessibility with the population within a 7.5 km radius. Not all streets are particularly suitable for cycling in cities. In our analysis, we excluded roads where cycling is not allowed (mostly urban motorways) and assumed that some bike-friendly rules are applied, such as contraflow cycling in one-way streets or (low-speed) access to pedestrian areas. We applied this assumption because no reliable detailed data were available about such rules. We tested the effect of contraflow cycling on accessibility within 30 minutes by comparing two scenarios. In the first scenario, cyclists have to respect all one-way signs without exception. In the second scenario, contraflow cycling is allowed in all one-way streets. The accessibility gain under scenario 2 depends on the size of the city. In most cities of below 1 million inhabitants, contraflow cycling increases accessibility by 2 to 5%, while in larger cities the gain can be even higher than 10%. Finally, we adjusted the cycling speed in streets with steep slopes.

The estimated cycling performance for trips within 30 minutes shows an average of 75. Hence, in principle, cycling performs much better than public transport, at least for trips of a relatively short distance. The absence of waiting times, inherent in the use of public transport, is definitely a key element for explaining the difference. Nevertheless, the reported cycling performances are theoretical values based on relatively simple assumptions regarding network suitability. Cycling accessibility may be lower in case of poor road conditions or the unsuitability of certain streets, for instance due to poor safety conditions. On the other hand, even in cities where geographical obstacles are common, cycling conditions may actually be better than expected. For instance, Amsterdam and Copenhagen, both well-known cycle-friendly cities, score low on the performance indicator because of the presence of canals and other waterways that result in detours when cycling (figure 10).

A more in-depth analysis of walking and cycling opportunities would require more and better data which falls outside the scope of this paper. The actual walkability of the street network depends on numerous factors, including the presence and state of appropriate walkways, pedestrian-friendly and safe street crossings, objective and subjective safety, and the attractiveness of the surroundings¹⁹. Furthermore, evaluating the suitability of street networks for cycling requires more information than what is currently available from mainstream road network datasets (for instance, information on traffic-calming measures, dedicated lanes, right turn on red²⁰, etc.).

¹⁸. FLOW project (2016).

¹⁹. Abstracts of case studies on walkability and cycle-friendly policies in Toivonen et al. (2019).

²⁰. Left turn on red in countries with left-hand driving.

FIGURE 9: Performance of walks up to 30 minutes

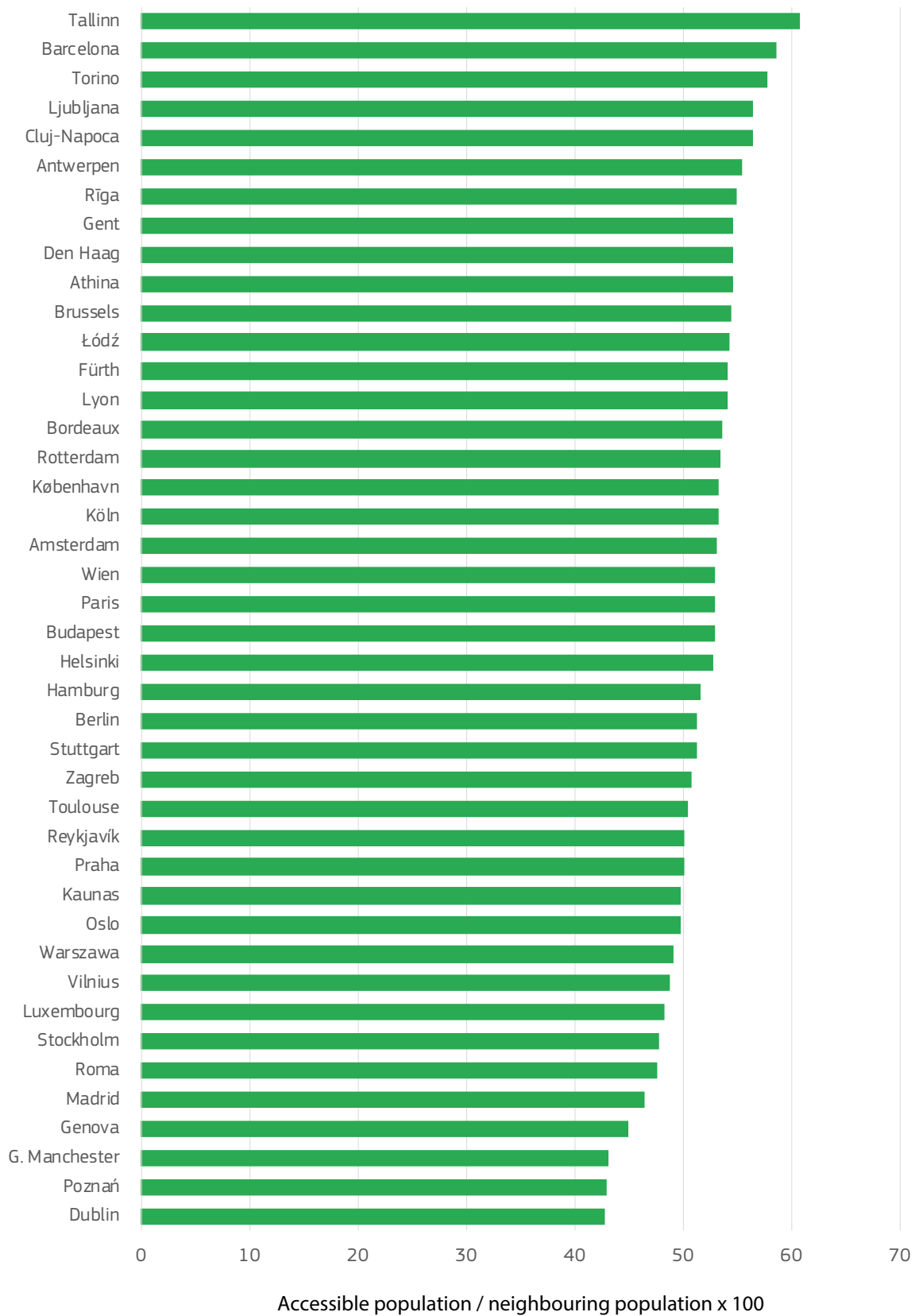
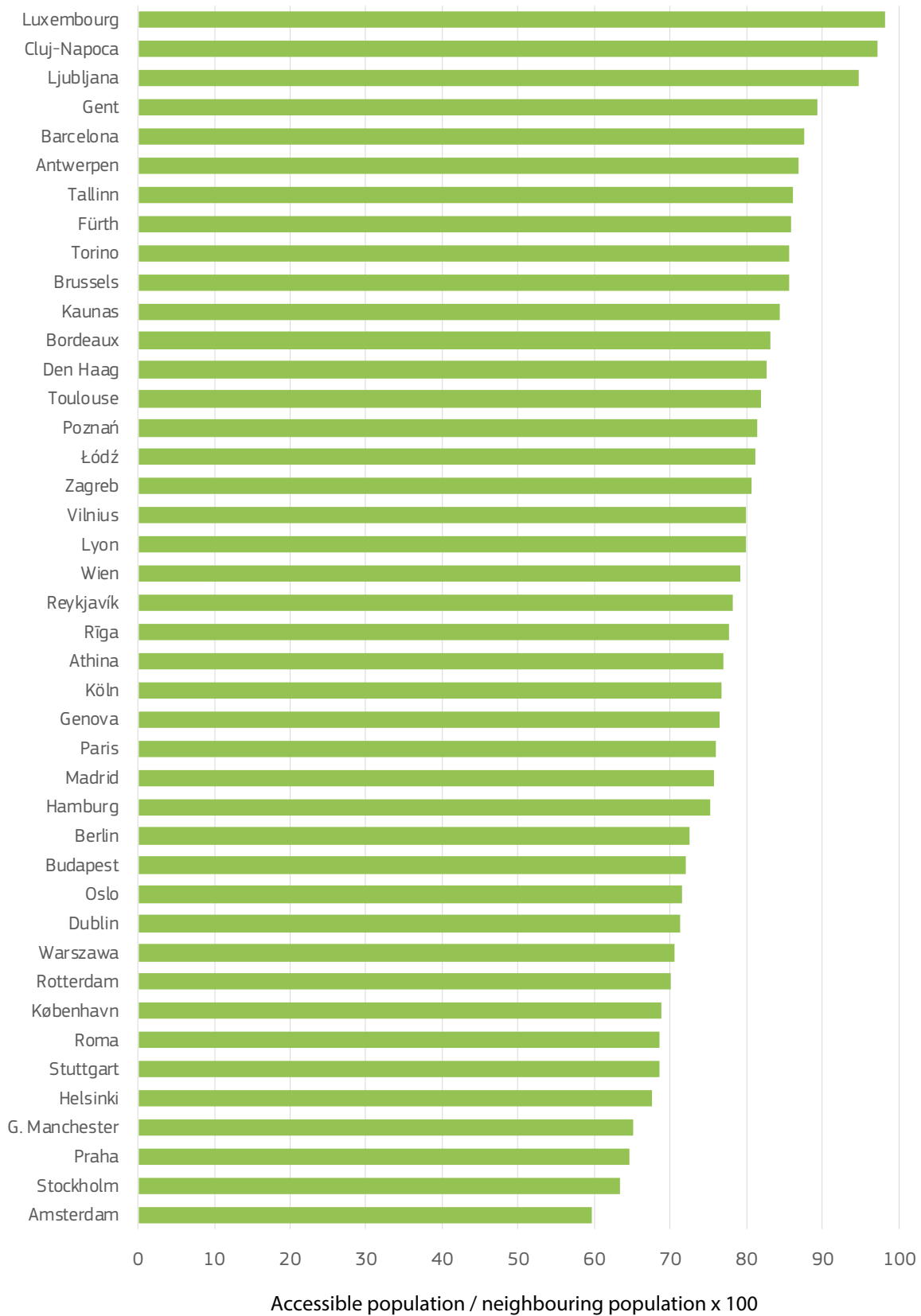


FIGURE 10: Performance of bike rides of up to 30 minutes



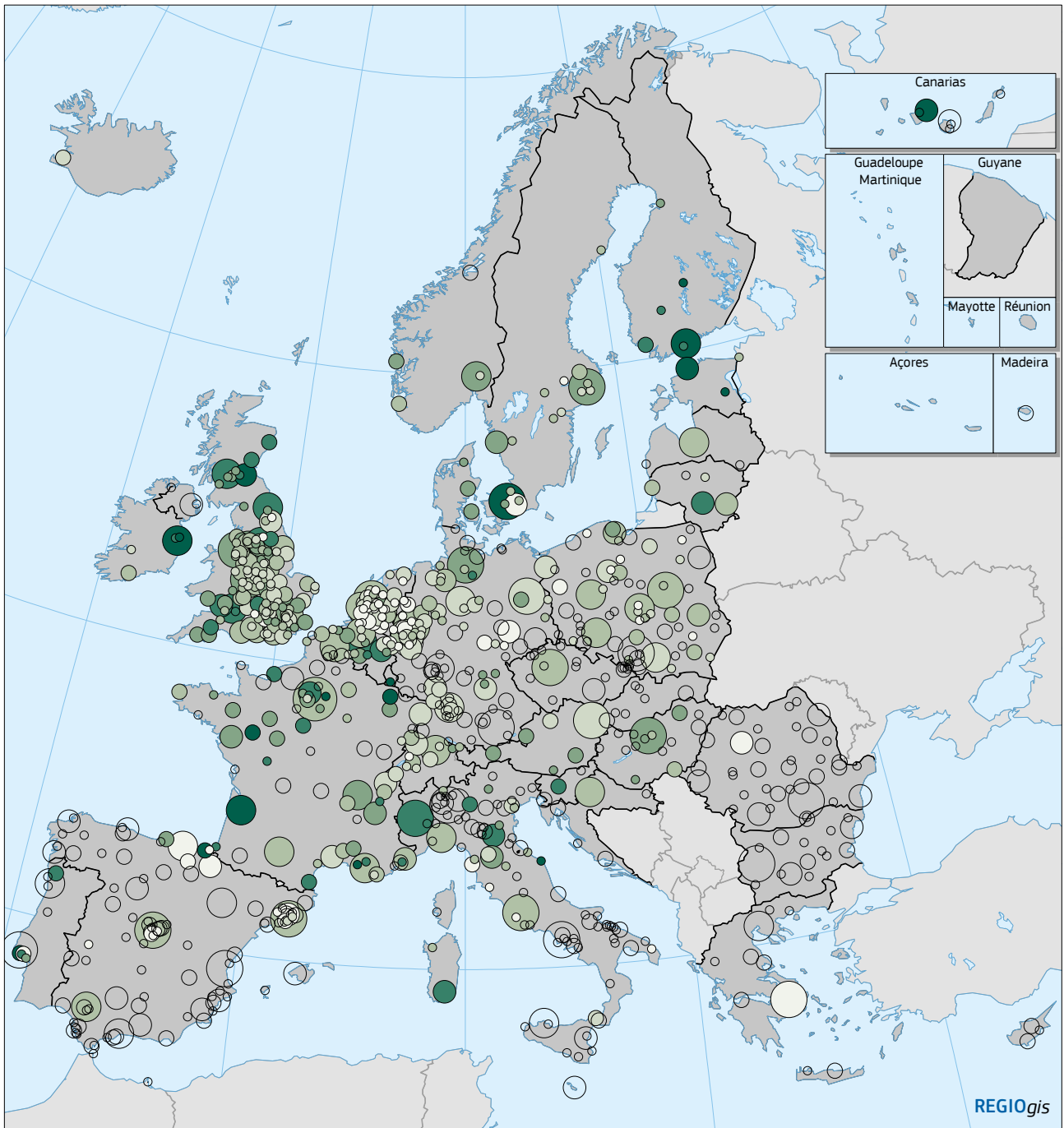
4. PERFORMANCE OF PUBLIC TRANSPORT AND ACTIVE MODES: SOME CONTEXT INDICATORS

4.1 PUBLIC TRANSPORT VEHICLE KILOMETRES TRAVELLED

Using the scheduled timetables for urban public transport combined with the location of the stops we were able to estimate the total length of all public transport vehicle trips between 6:00 and 20:00 on a weekday. This metric can help contextualise the indicators on the frequency of departures, accessibility and transport performance. As map 5 shows, the

total length of all vehicle trips inside urban centres varies widely when expressed in kilometres per thousand inhabitants. While vehicle kilometres travelled is obviously related to the frequency of the services, it is also influenced by the layout of the urban street network, the kind of vehicles operated and their capacity. For example, a single high-capacity metro trip can replace many bus trips. Unfortunately, data on the capacity of each vehicle is not available.

MAP 5: Public transport vehicle kilometres per inhabitant in urban centres



Public transport vehicle kilometres in urban centres, 2018

km / 1000 inh.	Urban centre population
○ < 7	○ < 100000
○ 7 - 10	○ 100000 - 250000
○ 10 - 13	○ 250000 - 500000
○ 13 - 17	○ 500000 - 1000000
○ 17 - 21	○ 1000000 - 5000000
○ ≥ 21	○ ≥ 5000000
○ No data	

Straight-line distance of trip segments in the urban centre on a weekday between 6:00 and 20:00.
Sources: public transport operators, REGIO-GIS

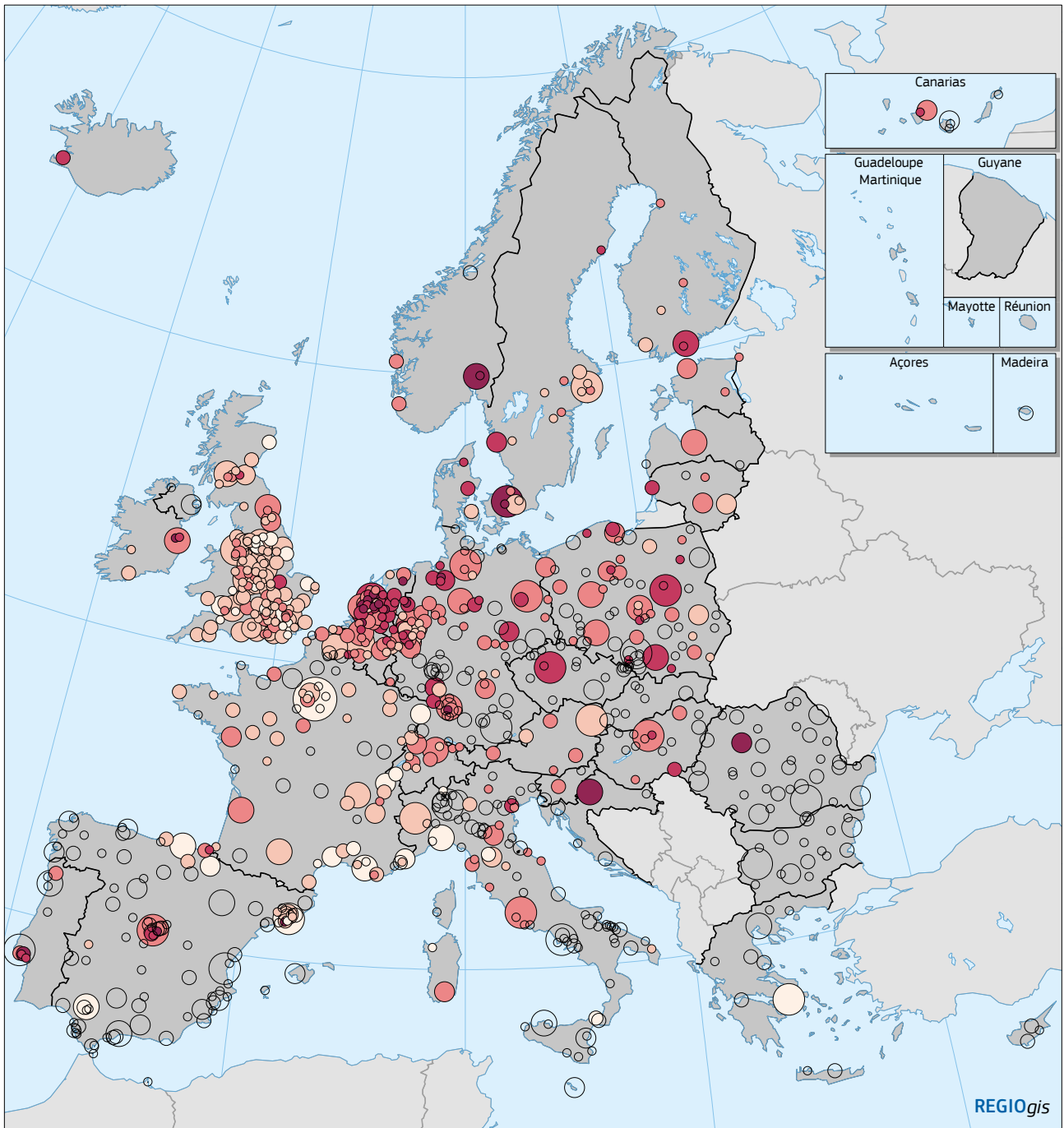


4.2 AVERAGE SPEED OF SCHEDULED PUBLIC TRANSPORT TRIPS

The analysis of vehicle kilometres travelled also provides estimates of the speed at which the vehicles operate. It is useful to note that the estimated speed is measured along straight lines connecting one stop with the next one within each scheduled trip. In the real world, the line between two subsequent stops will rarely be exactly straight. As the actual distance travelled between two stops is often longer than a straight line drawn between the two, the straight-line speed somewhat underestimates the actual speed of the vehicle.

Although the average speed of all public transport vehicles can be computed, it is probably more relevant to look at the average speed by transport mode. On map 6, we depict the average straight-line speed of all bus trips between 6:00 and 20:00 on a typical weekday. The average bus speed in the observed cities is around 14.5 km/h., although there are also many cities where the scheduled average speed is lower than 12.5 km/h. These cities house 25% of the population in all urban centres for which we have timetable data. On the other hand, in cities like Copenhagen, Cluj-Napoca and Oslo, buses travel at speeds of over 20 km/h. Bus speed is definitely influenced by the street network layout and by the use of infrastructure facilitating bus traffic flow (timing of traffic lights, traffic lights pre-emption, separated right of way). Improving the ease of boarding can also play a role, for instance by platform-level boarding or by using low-floor buses.

MAP 6: Average straight-line speed of bus trips in urban centres



Average speed of bus vehicle trips in urban centres, 2018

km/h	Urban centre population
○ < 12.5	○ < 100000
○ 12.5 - 15	○ 100000 - 250000
○ 15 - 17.5	○ 250000 - 500000
○ 17.5 - 20	○ 500000 - 1000000
○ ≥ 20	○ 1000000 - 5000000
○ No data	○ ≥ 5000000

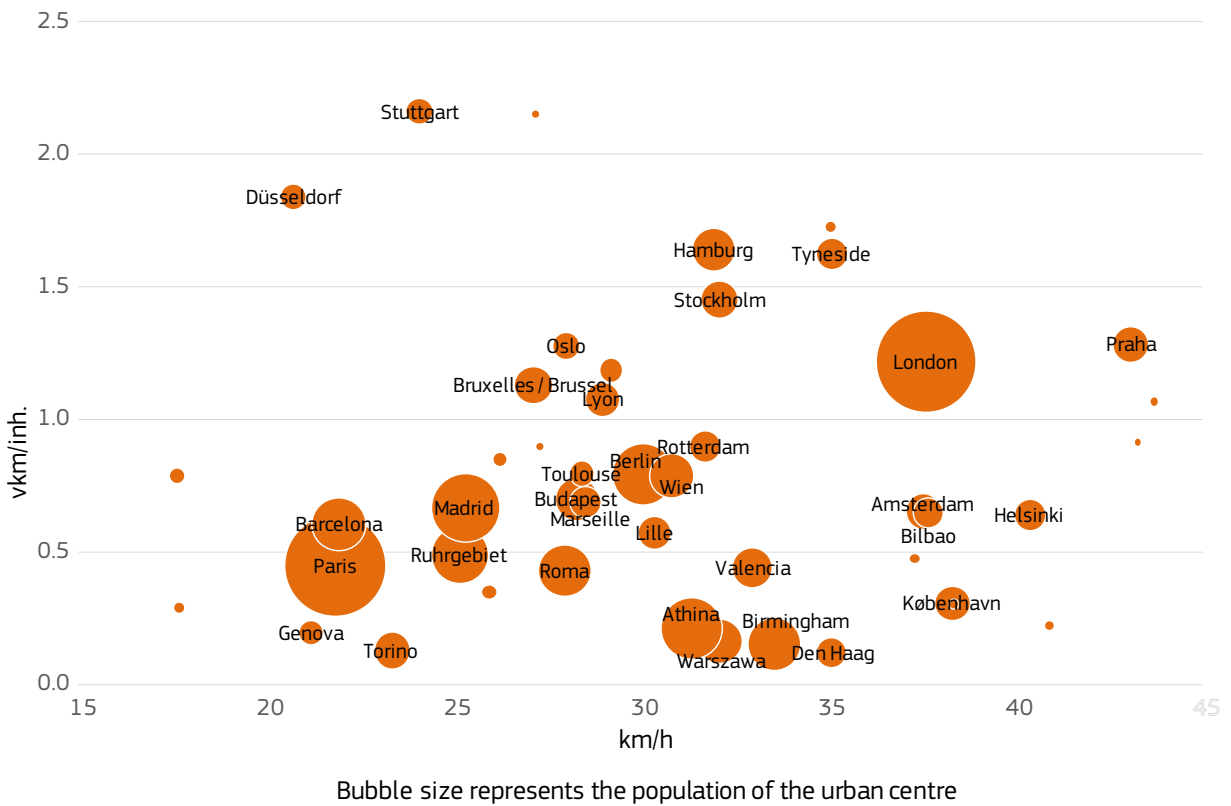
Speed measured along straight lines connecting bus stops in urban centres. Average according to timetables on a weekday between 6:00 and 20:00.
Sources: public transport operators, REGIO-GIS



The obstacles encountered by bus traffic are absent in the case of metro networks. Despite this, the average speed of vehicles on metro networks shows a wide variation. Figure 11 combines the average speed with the vehicle kilometres per inhabitant. A combination of high speed and high vehicle km/inhabitant, as seen in Prague and London, indicates a performant metro network that plays an important role in providing mobility services. At first glance, the network in Paris performs less well than that in London. However, it is important to bear in mind that Paris also benefits from an important sub-urban rail

network operating at a higher average speed (52.7 km/h) and contributing 1.0 vkm (vehicle kilometres)/inhabitant. In some cities, the distinction between sub-urban rail networks, metro and tram networks is not straightforward²¹. Sub-urban rail in urban centres offers frequent rides (more than 2 vkm/inhabitant) in Copenhagen, Oslo, Greater Manchester, London, Glasgow, Helsinki and Zürich. Trains on such networks operate at straight-line speeds of more than 50 km/h in Ruhrgebiet, Solingen/Wuppertal, Oslo, Paris and Birmingham.

FIGURE 11: Average straight-line speed and vehicle kilometres travelled by metro systems

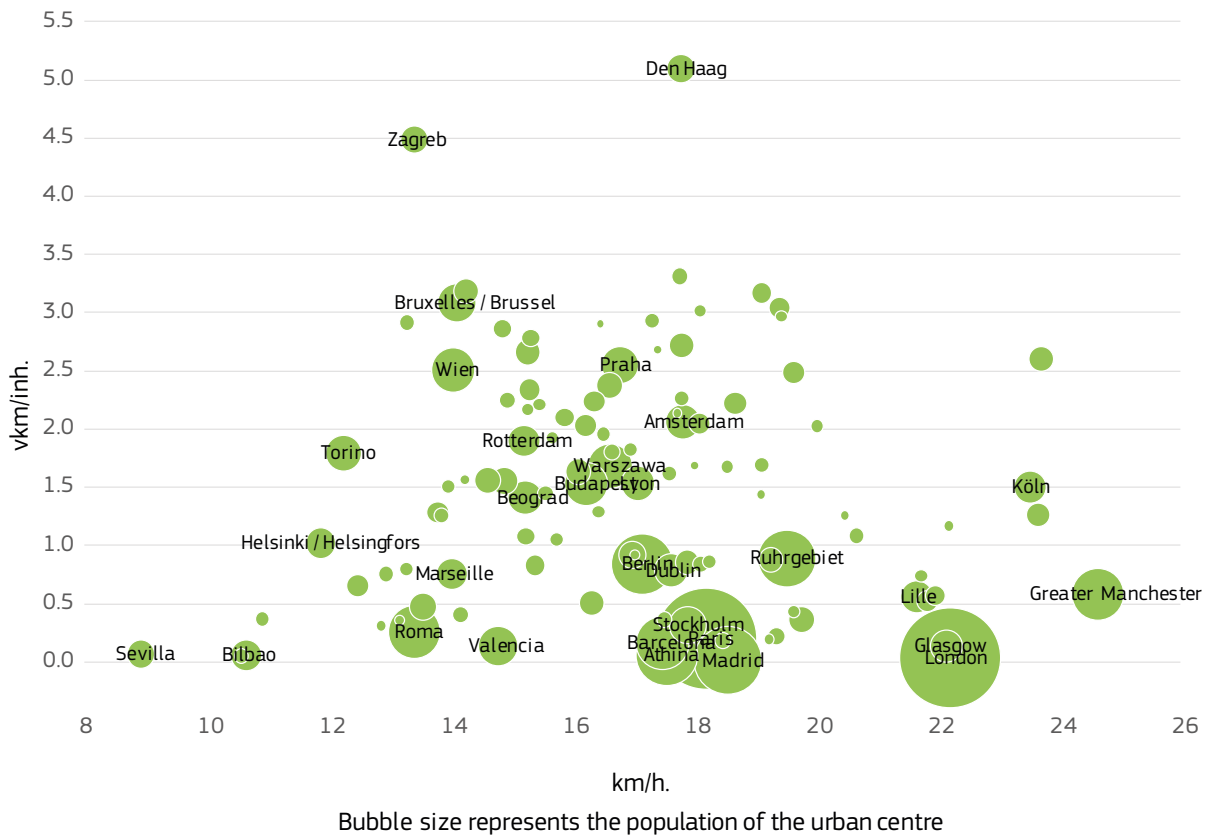


²¹ We used the classification provided by each of the providers of General Transit Feed Specification (GTFS) timetable data. The methods used by providers to encode the transport modes of their trams, metro or suburban rail services are not harmonised.

Speed and trip-length performance of tram systems are illustrated in figure 12. The average straight-line speed exceeds 20 km/h in some cities, although in many cases the tram lines only account for a small number of vehicle kilometres per inhabitant. Trams play an important role in cities like Zagreb,

The Hague, Brussels, Vienna and Prague, with quite a good speed performance in The Hague and Prague. The presence of network segments with separate right of way can seriously influence the scheduled tram speed.

FIGURE 12: Average straight-line speed and vehicle kilometres travelled by trams

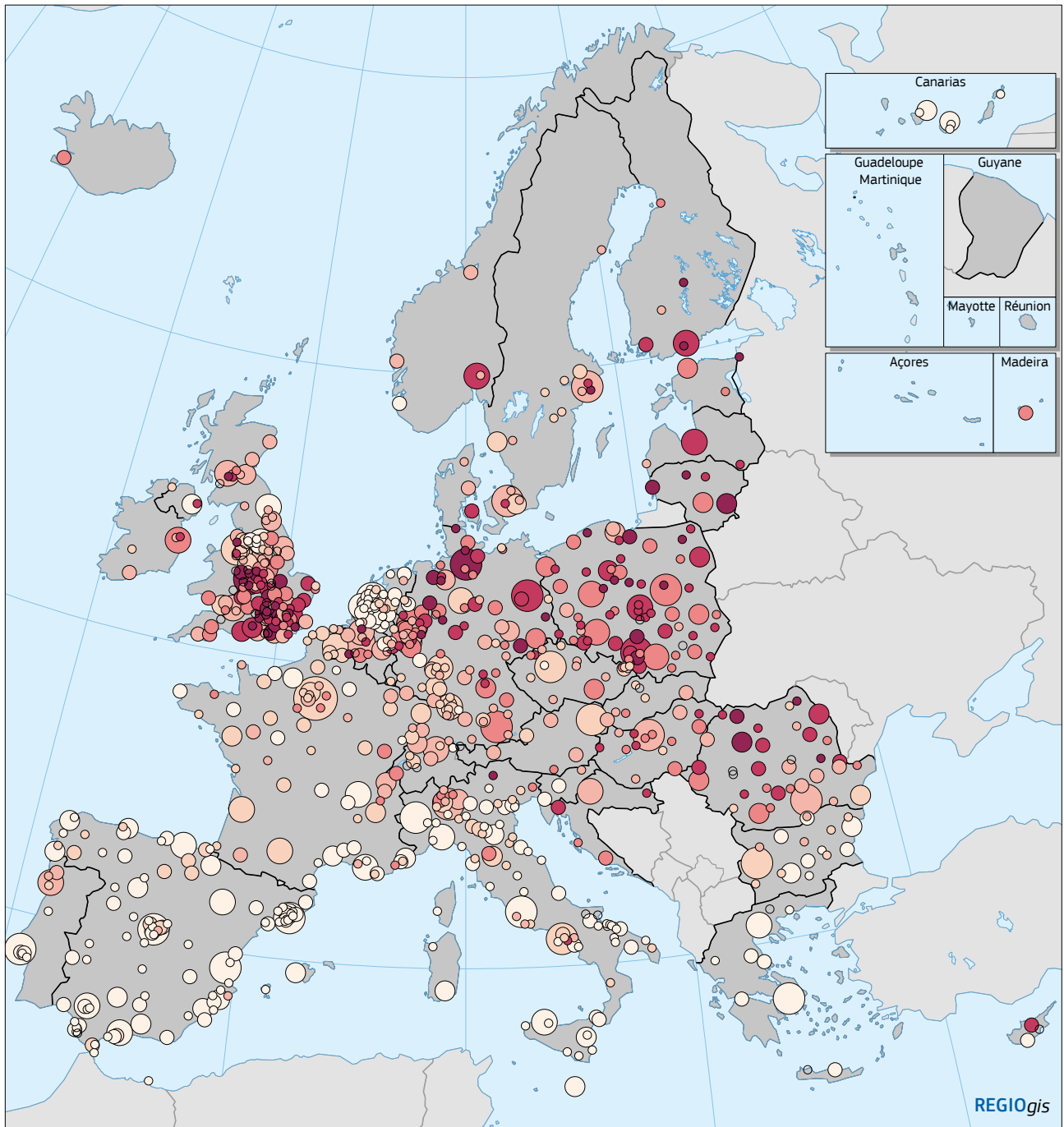


4.3 MEDIAN BLOCK SIZE

A dense street network tends to favour opportunities for walking and cycling, offering more choices on how to reach a destination while avoiding detours. Using comprehensive land-use/land-cover data from the Copernicus Urban Atlas, we measured the size of all urban blocks. We defined an urban block as the (smallest) area surrounded by streets. The higher

the surface of the blocks, the coarser the street network. Map 7 shows the median block size (in m²) by urban centre: half of the blocks in an urban centre have a surface less than the surface shown on the map. Most of the cities in southern Europe have a dense network with (very) small blocks, which favours walking. Small blocks are also typical for most of the cities in the Netherlands, while other countries show more variety in block size by city.

MAP 7: Median block size in urban centres, 2012



Median block size in urban centres, 2012

m ²	Urban centre population
○ < 9000	○ < 100000
○ 9000 - 12000	○ 100000 - 250000
○ 12000 - 15000	○ 250000 - 500000
○ 15000 - 18000	○ 500000 - 1000000
○ 18000 - 22000	○ 1000000 - 5000000
○ >= 22000	○ >= 5000000
○ No data	

Median surface of urban blocks, i.e. the smallest area surrounded by streets.
Sources: Copernicus Urban Atlas, REGIO-GIS

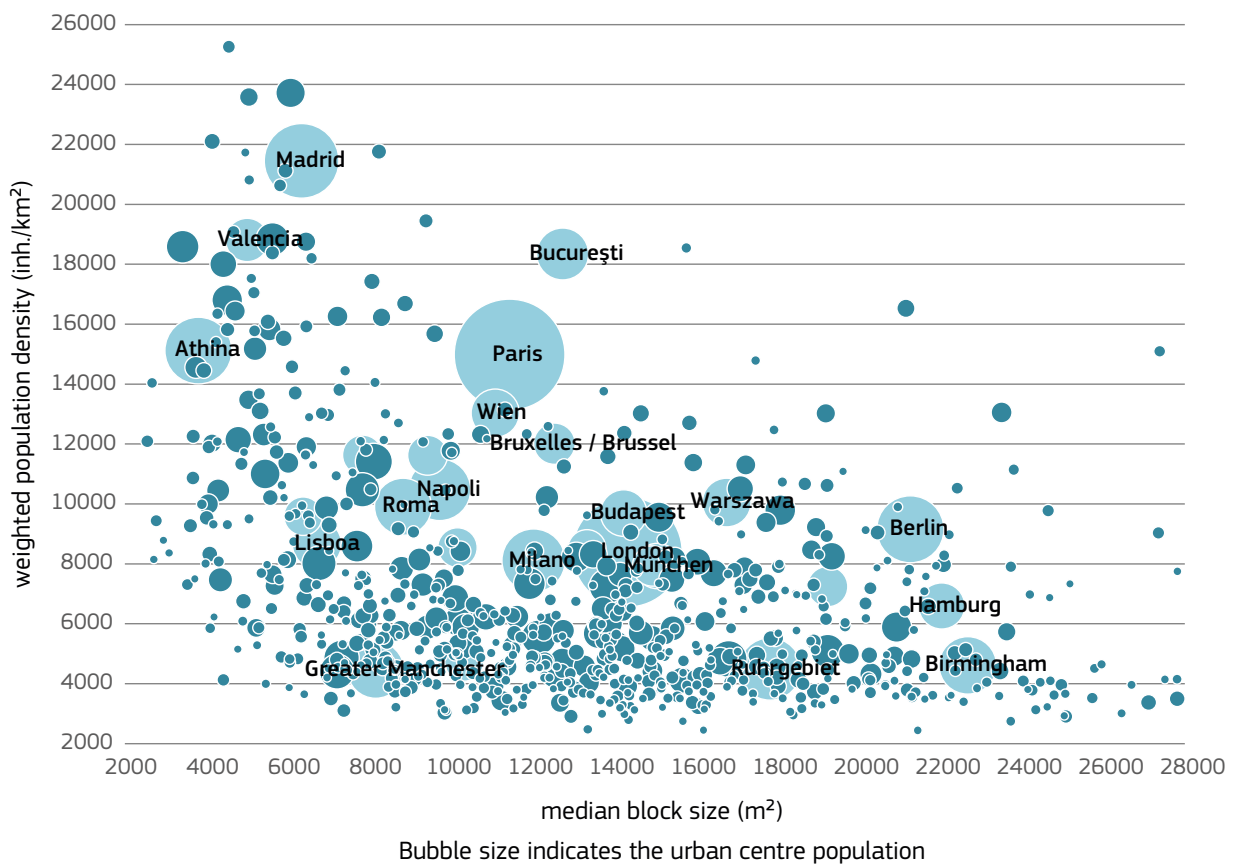


4.4 WEIGHTED POPULATION DENSITY OR NEIGHBOURHOOD DENSITY

By definition, urban centres have a population density of more than 1 500 inhabitants/km². However, this density does not provide any information about the relative population concentration or dispersion within the city. In a city where population is mainly concentrated in a few hot spots, providing efficient transport services may be easier than in other cities²². Active mobility performance may also be favoured by highly concentrated population patterns. The weighted population density is a measure of concentration of population inside a given territory. Computing this metric preferably requires a uniform spatial breakdown of the city. Within each urban centre we take to population-weighted average of the population density, measured at the level of 1 km² grid cells. Comparing two hypothetical cities with the same population density, the city in which more people live in high-density grid cells will have the highest weighted density of the two. Map 8 shows the diversity in population concentration within each urban centre. High population concentration inside urban centres is mainly found in Southern and Eastern Europe. Elsewhere, relatively high weighted density is found in larger cities like Paris, Vienna or Brussels.

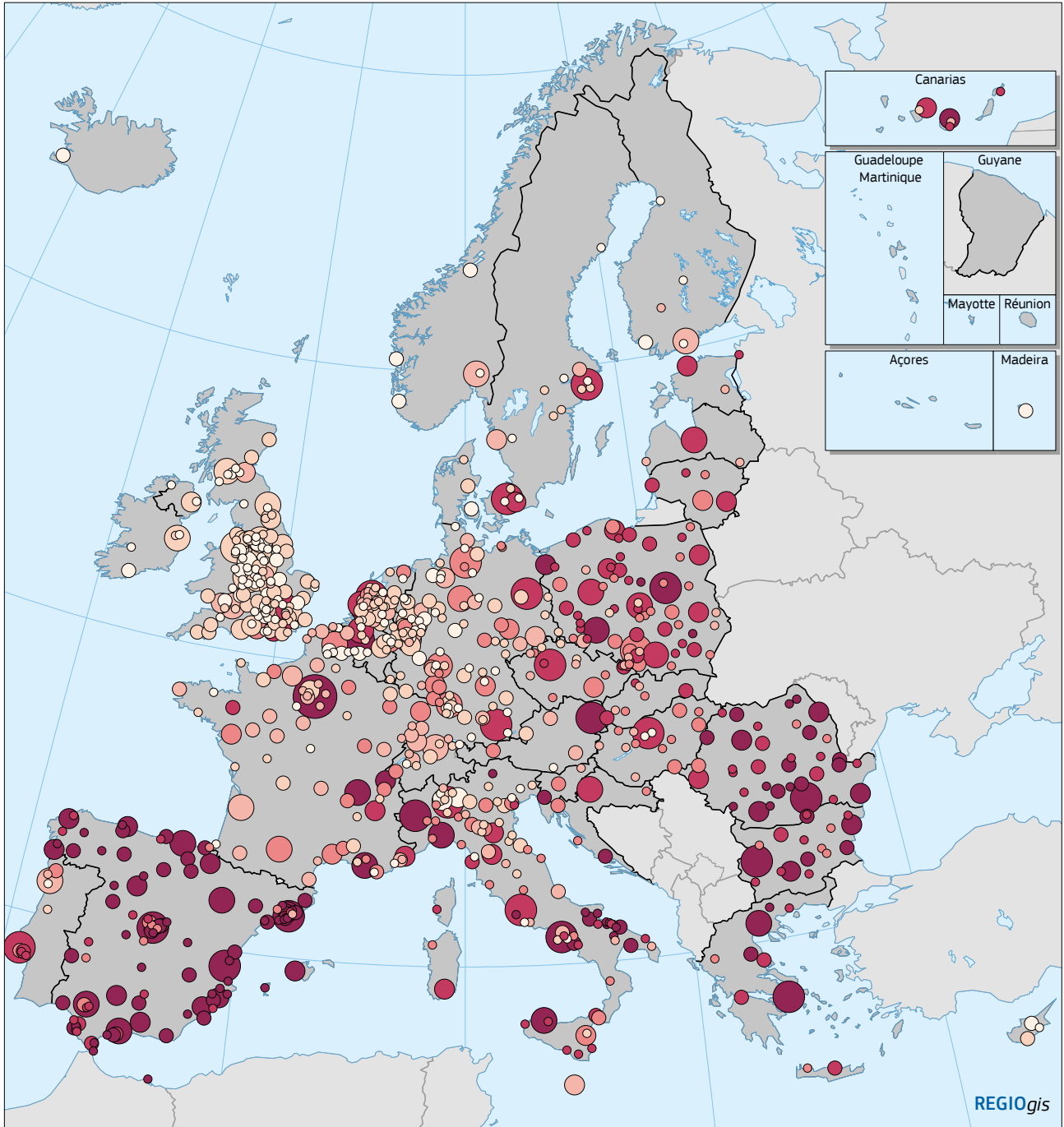
Block size and weighted population density are somewhat related although the relationship is not very strong, as shown on figure 13. Some major southern cities (e.g. Madrid, Valencia, Athens) have a highly concentrated population and an urban fabric characterised by small building blocks. In principle this combination favours walking. On the other hand, cycling is expected to be a more appropriate active mobility mode in cities like Berlin, Hamburg or Birmingham, where the median block size is higher and the population concentration lower.

FIGURE 13: Median block size and weighted density by urban centre



²² See also Chapter 6 (Resource-efficient cities), pp. 140-155 of the State of European Cities Report: European Commission and UN-HABITAT (2016).

MAP 8: Weighted population density by urban centre, 2011



Weighted population density by urban centre, 2011

Inhabitants/km ²	Urban centre population
○ < 4000	○ < 100000
○ 4000 - 5000	○ 100000 - 250000
○ 5000 - 6000	○ 250000 - 500000
○ 6000 - 7500	○ 500000 - 1000000
○ 7500 - 10000	○ 1000000 - 5000000
○ ≥ 10000	○ ≥ 5000000
○ No data	

Population-weighted average of population density at the level of 1 km² grid cells.
Sources: Eurostat (GEOSTAT 2011 grid), DG REGIO



5. DATA CHALLENGES AND OPPORTUNITIES

Adequate input data are essential for a successful analysis. In particular, the street network must be complete, not only in terms of the network segments layout (i.e. all streets, lanes, paths), but also in terms of the attributes (particularly those that indicate suitability for walking or cycling). Ideally, authoritative, complete, up-to-date and freely available networks applying harmonised data models should be available²³. Alternatively, volunteered collaborative datasets, such as OpenStreetMap (OSM) or commercial road network datasets, can be taken into consideration. In all cases, the networks should be exploitable by routing tools, adequate for public transport, walking and cycling routing computations.

Appropriate network data combined with high-resolution geospatial data on land use and environmental indicators will provide opportunities to better assess walkability and highlight the differences in attractiveness for walking and cycling throughout cities' territories. For instance, the use of Copernicus Urban Atlas could be tested to characterise the 'greenness' of the street network related to the presence of nearby green areas²⁴.

Public transport analysis is further challenged by the availability and harmonisation of timetable data and the location of stops. a growing number of transport operators and regional and national data integrators have made significant efforts to provide open and up-to-date data according to a de-facto standard. Despite this, timetables are still unavailable for large parts of the European territory and standardisation of the data models can and should be improved. The data landscape is also quite fragmented, often requiring time-consuming efforts by analysts to find the right data and make them fit for use²⁵.

Transport availability and performance metrics should also be accompanied by data on the use of the networks and citizens' perceptions of their quality. The forthcoming survey on the quality of life in European cities will provide a harmonised framework that will help to answer these questions²⁶.

Throughout this paper, we have analysed urban centres (high-density clusters) to ensure comparability of the results. When assessing proximity, accessibility and transport performance, we have treated urban centres as closed systems, i.e. we have only considered what happens between places inside the same urban centre. Better availability of harmonised timetable data will enable us to gradually overcome this limitation. Providing that adequate computing resources are available, future analysis could also look into destinations around urban centres that can be reached within reasonable travel times. In addition, differences in accessibility and transport performance could be analysed by taking various time frames into account, for instance during peak hours, off-peak or during weekends. While we have focused on a high spatial resolution (building blocks) within urban centres, further tests may be worth pursuing with a wider range of time and distance thresholds as well as calculating accessibility for more points.

As the analysis relies upon the spatial distribution of population and employment, high-resolution data on both metrics are required. We think that a high-resolution spatial framework such as the building blocks used by the Copernicus Urban Atlas is an appropriate spatial level for this analysis. However, using such a framework poses the challenge of creating useful population and employment data at that level. In practice, bottom-up, address-based population or employment counts can seldom be obtained at building-block level. Disclosure control constraints will probably always limit the availability of these bottom-up data for small patches of territory. Alternatively, when bottom-up counts are not available, downscaling methods must be applied to estimate figures at the building-block level. By combining input data at the best available spatial resolution with ancillary data on land cover, land use, and – preferably – data on the location, function and height of buildings, estimates of a useful quality can be obtained. The perspective of a regular (annual) production of a 1 km² (residential) population grid is a very promising evolution. Finally, innovative combinations of administrative sources and big data, like mobile phone location data, may provide opportunities to better understand the spatial distribution of daytime population.

²³ Such datasets, compliant with INSPIRE data models, are in principle part of the foreseen deliverables of the access points of the Multimodal Travel Information Services (MMTIS), see: Commission Delegated Regulation (EU) 2017/1926 of 31 May 2017 supplementing Directive 2010/40/EU of the European Parliament and of the Council with regard to the provision of EU-wide multimodal travel information services: http://data.europa.eu/eli/reg_del/2017/1926/oj

²⁴ Similarly, a 'Green View Index' has been developed by the MIT Senseable City Lab: <http://senseable.mit.edu/treepedia> and <https://toolkit.climate.gov/tool/treepedia>; see also Li et al. (2015).

²⁵ The successful implementation of the MMTIS data access points accompanied by adequate openness of the data therein will be an essential prerequisite for mainstreaming the proposed methodology throughout the whole EU territory.

²⁶ See: European Commission (2016) for the report on the previous edition of this survey. The data can be consulted at: https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=urb_percep&lang=en

CONCLUSIONS

Ten years ago, this analysis would not have been possible. Only now that we have public transport timetables in a standardised, machine-readable format, a detailed population grid, a harmonised definition of a city, and a comprehensive street network have we been able to calculate access to public transport for so many cities. This wealth of information allows us to compare a wide range of European cities in terms of access to public transport, key characteristics of the public transport system (median departures, speed, vehicle km travelled) and of the city (block sizes, neighbourhood density). The city fact sheets accompanying this working paper provide a good overview of public transport performance.

The comprehensive information in this working paper represents an important first step in understanding public transport performance in European cities. Subsequent analysis should focus on the key determinants of this performance and how to improve it.

Nevertheless, a significant number of cities are still missing, especially in less-developed regions and Member States. To carry out further work requires that public transport data are made available for all cities and are regularly updated. In combination with annual population grids and up-to-date street networks, access to public transport and its performance can be monitored over time.

More data on specific services, the location of jobs and daytime population would enable us to assess how well public transport serves these important destinations. A first assessment carried for a limited set of cities shows that, in general, access to jobs and the daytime population tends to be better than for residential populations.

METHODOLOGY

ACCESS TO PUBLIC TRANSPORT STOPS

To compute the SDG 11.2.1 core indicator, we needed comprehensive data on the location of public transport stops, a complete street network, and data on the spatial distribution of populations inside the cities.

Data on the location of public transport stops is available from a wide variety of sources, but data availability and completeness varies by country and/or region. This situation resulted in the following ranking of preferred data sources:

1. Integrated (authoritative) datasets providing stop locations and scheduled timetables for all public transport in an entire country (or region).
2. Datasets providing stop locations and scheduled timetables for major transport operators in a particular region or city.
3. Datasets from authoritative sources, providing stop locations in a particular country or region (without data on scheduled timetables).
4. Volunteered geographical information data on stop locations (OSM).

The location of stops can be portrayed in various ways depending on the input datasets. For instance, if a bus stop is located on both sides of a street (i.e. a stop for each direction), some datasets will consider this to be one single stop, while others will provide separate data for the actual location of each stop. Something similar happens when representing bus stations or railway or metro station platforms. In order to create more homogeneity in the data and enhance the comparability of the results, we identified all stops located within 50 metres from another stop. All stop points located very close to each other were seen as a single cluster of stops. Each cluster was represented by a single point, located at the centre of the clustered stops. All further steps in the methodology used clustered stops, which we simply referred to as stops.

In the absence of any other source of stop locations, it was hard to assess the completeness of OSM stops data. We obviously wanted to avoid taking into consideration incomplete data for a city. To assess the plausibility of the OSM data completeness, initially we carried out a statistical analysis by city. We extracted all OSM points representing stops, platforms or stations, clustered the nearby stops and overlaid these with the

urban centres' boundaries. Next, we computed the number of stops per urban centre and their density per square kilometre. We did the same analysis on the basis of stop datasets from authoritative sources. By carefully observing the range and distribution of the stop densities (also in relation to the cities' total populations) observed in both the authoritative and the volunteered sources, we decided to exclude OSM data for cities where the density clearly lays below any reasonable value. Furthermore, for all urban centres where OSM data could potentially be used, we performed a cartographic examination of the spatial distribution of the stops relative to the extent of the urban centre and the topographic features of its territory.

Assessing proximity to public transport stops requires a complete street network, including attributes enabling a selection of streets accessible to pedestrians. We considered the content and coverage of TomTom MultiNet data appropriate for this purpose. For each of the countries/regions/cities where stop data were available, we built a GIS road network dedicated to pedestrian use. Next, using this network, a service area of 500 metres' walking was computed around each stop. These service areas partly overlapped in many places. Merging the overlapping areas produced two kinds of areas in an urban centre: 1) areas close to stops; and 2) areas further away from stops.

Finally, the calculation of the SDG indicator requires high-resolution data on the distribution of a city's population. Such data can be grid-based or related to (small) polygons. For most of the urban centres, data on urban land use/land cover are available in the Copernicus Urban Atlas 2012 layer. In urban centres, polygons of this data source correspond to building blocks, defined as polygons containing built-up areas and delimited by streets or other features. These building blocks are an adequate unit of analysis because of their tight integration in the street network. For each of the building blocks, an estimate of residential (night-time) population was computed with the reference year 2011²⁷. In areas without Urban Atlas data coverage, we used population estimates by 100 x 100 metre grid cells²⁸.

In subsequent steps of the workflow, some calculations assumed area-weighted distributions inside polygons. Therefore, it is preferable that all layers used in this project were stored in an equal-area projection²⁹. All populated areas in a city were intersected with service areas depicting the areas close to public transport stops. Finally, within the boundaries of each urban centre, the population was summed in: 1) areas close to the stops; and 2) areas further away than a 500-metre walk to any stop.

²⁷. Batista e Silva and Poelman (2016).

²⁸. Freire, Halkia and Pesaresi (2016).

²⁹. Lambert azimuthal equal-area projection (GCS ETRS 1989), EPSG:3035.

ACCESS BY FREQUENCY OF PUBLIC TRANSPORT DEPARTURES

To assess the frequency of the transport services provided at walking distance, we needed machine-readable scheduled timetable data that could be combined easily with stop location data. An increasing number of timetable datasets is available according to the General Transit Feed Specification (GTFS)³⁰, including stop location data, timetables, information about the transport mode and dates of the services' activities. Some other datasets are disseminated in nationally defined data specifications and have had to be transformed into the GTFS specification³¹.

It was necessary for all GTFS datasets to undergo an extensive validation process. The GTFS model comprises different tables linked by common attributes. Checks were necessary to ensure that the values of these attributes matched the linked tables. Further checks of the completeness of the schedule information (dates of service operations) and of the actual timetables were also necessary. Some datasets did not contain departure times for all stops during a trip. In these cases, we had to interpolate the missing departure times. Furthermore, the route types (i.e. the transport modes) had to be harmonised, distinguishing only bus, tram, metro, train and ferry³². In the end, a few GTFS datasets failed the validation tests and could not be used for further analysis.

Our analysis focused on services provided during weekdays. From the GTFS stop-time tables, we selected all departures between 6:00 and 20:00. The actual calendar day selected depended on the availability of timetable schedules in the input datasets. Each of these datasets refers to its own period of validity. Within that period, we identified the day with the maximum number of departures. As service frequencies are typically highest during weekdays, selecting the day with the maximum number of departures avoids public holidays, weekends or school holidays.

Whilst the core SDG indicator treats all public transport stops in the same way, we have distinguished two groups of transport modes, each with their stop locations and timetables.

Group 1 covers bus and tram. Group 2 includes metro, mainline rail and suburban rail. We created this distinction to take into account the differences in vehicles' operational speed. We decided to combine tram with bus despite the fact that some newer tram lines can perform better than bus lines. In city centres, in particular, tram services are often subject to congestion problems.

For each combination of stop location and group of transport modes we calculated the average number of departures per hour. If a stop location represented a cluster of nearby stops, the departures of all clustered locations were summed. Then we created service areas around the stops: service areas of 500 metres' walking around bus and tram stops, while a 1-km walk was used around metro and train stops.

Within each of the service area groups (bus and tram versus metro and train) the areas tended to partly overlap each other, especially in a dense urban environment. In these overlapping areas, people had the choice between two or more stops nearby. Frequencies could be different at each of these nearby stops: if this occurred, we assumed the stop with the most frequent departures to be the most probable choice. This means that we intersected the service areas within each group of transport modes and attributed the maximum value of the number of departures to the overlapping areas³³. Within each group of transport modes, this result shows the best available level of service frequencies at any area in the urban centre.

For the creation of a typology of proximity and service frequencies, we first reclassified the frequencies within each transport mode group into four service level categories (figure 14):

FIGURE 14: Frequency of departures by transport mode groups

	Rail and metro/Bus and tram
No services	Outside service areas
Low frequency	Less than 4 departures an hour
Medium frequency	>= 4 and < 10 departures an hour
High frequency	More than 10 departures an hour

³⁰ <https://developers.google.com/transit/gtfs/>

³¹ Despite the standard GTFS data model, datasets are provided at various levels of aggregation (for instance, one dataset per operator, an integrated dataset for a single region or a single integrated dataset for an entire country). For our analysis, we used datasets from more than 125 sources.

³² Some GTFS datasets contain an extended classification of transport modes (route types), distinguishing many different types of bus or train services (see: <https://developers.google.com/transit/gtfs/reference/extended-route-types>).

³³ In some areas, mainly located along national borders, the overlapping of service areas defined around public transport stops may also occur if the area is serviced by cross-border operators. The same timetables for cross-border services might be included in more than one input dataset. Hence, in these (small) areas, some uncertainty persists as regards the actual scheduled number of departures per stop. In the current state of data availability, this is inevitable, because of the large variety of data sources that were required. Although our best efforts were made to avoid overlaps in timetables of (adjacent) service providers, they cannot be excluded entirely.

Via an intersection of the reclassified service areas of each of the transport mode groups we obtained a set of areas containing the combination of frequency classes, i.e. a matrix of 16 possible classes. Some of these were grouped to obtain a final typology with five frequency categories:

- ▶ Very high: access to more than 10 departures an hour for both transport mode groups;
- ▶ High: access to more than 10 departures for one group of modes but not for both;
- ▶ Medium: access to between 4 and 10 departures an hour for at least one group of modes but no access to more than 10 departures an hour;
- ▶ Low: less than 4 departures an hour for at least one group of modes but no access to more than 4 departures an hour;
- ▶ No access: no easily accessible departures (by none of the modes), i.e. areas more than 500 metres from any bus or tram stop and over 1 km from any metro or train stop.

The intersected areas were then grouped according to the five typology categories. These areas were intersected with those containing the population figures. From the intersected areas, it was easy to obtain the urban population distribution by category of service frequency.

Apart from creating the frequencies typology, we could also create a distribution of urban centre population according to the total number of departures available within walking distance. From the two sets of service areas containing the absolute number of departures at nearby stops, we produced a single set of service areas by means of intersecting the two groups: where the two overlap, people have easy access to both bus or tram and metro or train. For each of those areas the maximum number of departures by bus and tram and by metro and train are known. Hence, the total number of easily accessible departures is thus the sum of both maxima.

By intersecting this result with the areas containing the population counts, the geographical distribution of population relative to the overall level of service frequencies available within walking distance was ascertained³⁴. This distribution can be summarised in a frequency table by urban centre. It is to be expected that the frequency distribution would be rather skewed and could contain outlier values. Therefore, we also derived the population-weighted median number of departures an hour from the frequency table.

³⁴ The service frequencies are converted to integer values before intersecting in order to obtain a manageable number of output polygons.

ACCESSIBILITY BY PUBLIC TRANSPORT (COMBINED WITH WALKING)

To compute accessibility by means of public transport we had to define the spatial and temporal resolution of the analysis and decide on some crucial parameters.

The spatial units of analysis for the accessibility assessment were the polygons of the Copernicus Urban Atlas 2012 datasets. Origin and destination points were derived from these datasets, i.e. a centroid point of each polygon³⁵. Polygons representing water bodies or road networks³⁶ were excluded. For each polygon, we estimated a population figure³⁷ which was allocated to the centroid point of the polygon. Where available, estimates of workplace-based employment or daytime population were also added as attributes of the centroid points. We only assessed accessibility inside the urban centres, which means we only selected the points falling within the urban centre boundaries.

Using the selected points, we created a table of origin/destination combinations, whereby all points in the urban centre are the places of origin, and all points with a population > 0 (or employment > 0 or daytime population > 0, if available) are the destinations.

SELECTION OF TIMETABLE DATA

As for the analysis of the number of departures by public transport stop (see above), the accessibility analysis required complete and routable timetable data in GTFS format. From the available GTFS datasets, it was not always obvious what transport provisions were included (bus, train, etc.). For instance, GTFS feeds for cities often do not include railway data. In cases such as these, multiple deliberations are possible: 1) there is only one railway station in the urban centre, so railway data does not need to be included because there cannot be any rail connections inside the urban centre; 2) multiple railway stations exist along with a separate GTFS feed; or 3) multiple railway stations exist but a separate GTFS feed for rail does not exist. In the latter case, a GTFS feed converted from UIC MERITS railway timetable data³⁸ was used.

Another difficulty is to judge the completeness of a GTFS feed. It is possible to detect the transport type from the GTFS files (by inspecting the 'route-type' parameter), but there is no way of detecting if all currently existing providers of a certain transport type are included in the dataset. The completeness was assessed by cartographic comparison of the stop locations, the city's urban fabric, and on the basis of the analysis results of the proximity of stops and the services frequency typology. Where we had serious doubts about data completeness, no accessibility analysis was performed.

A third difficulty is that the time frame coverage of available GTFS feeds is not always the same. This is particularly troublesome in cases where these GTFS feeds have to be combined (e.g. when it is necessary to combine them with the rail UIC MERITS feed). Manual adaptation of the reference date of the GTFS feed is then needed (e.g. to force all services to a certain date). Using the same date is mandatory for successful origin/destination calculations.

ORIGIN/DESTINATION CALCULATIONS AND AGGREGATION

To produce accessibility matrices from many-to-many points in a geographical area (in this case, in urban centres), we used open source OpenTripPlanner (OTP) software³⁹. The OTP server analyst extension requires an OSM 'osm.pbf' file when building the graph⁴⁰. For smaller countries, this osm.pbf file was usable as is, but for most countries it was much too large for the OTP to process, at least on the available infrastructure. Consequently, for cities in countries like France, Germany, etc. we decided to extract the desired area from the country's osm.pbf file using the open source tool 'osmconvert'. The OTP server version 1.2.0 was installed and run in a Linux cloud environment. However, since by default the OTP analyst extension does not return a trip initial waiting time when evaluating a routing request, the source code was adapted and recompiled to accomplish this. This initial waiting time was necessary in order to assess the total travel time. The OTP server was started with parameters adapted to the purpose of the analysis⁴¹.

All the selected origin-destination pairs travel times using public transport were calculated nine times, i.e. with requested departure times every quarter of an hour during a two-hour morning peak period, resulting in a temporal resolution of 15 minutes. Repeating the calculation process nine times adds to the computational burden but ensures a more realistic picture of expected travel times. In fact, it models the variety of waiting times before boarding and between legs of the journey, because of differences in service frequency. For each requested departure time, we got the total travel time by public transport combined with walking – i.e. the time that elapsed between the requested departure time and the actual arrival time at destination. This included the initial walking time to the departure stop, the waiting time before the first boarding, all legs of the journey if more than one leg was needed, the transfer time(s) between these legs, and the final walking time to the destination⁴². The combination with walking was required because the places of origin and destination represented populated building blocks, not stops.

³⁵ In case of concave or irregular polygons, the centroid points have been forced inside the polygons.

³⁶ Urban Atlas classes 12210, 12220 and 50000. This leaves a set of polygons that can potentially hold population or employment.

³⁷ Population estimates by the Urban Atlas polygon: Batista e Silva & Poelman (2016).

³⁸ <https://uic.org/passenger/passenger-services-group/merits-database>

³⁹ <http://www.opentripplanner.org>

⁴⁰ The OSM osm.pbf files were accessed from: <http://download.geofabrik.de/europe.html>

⁴¹ Routing parameters (other than the default ones): maxWalkDistance: 5000 / maxTimeSec: 3600 / clampInitialWait: -1 / streets: yes (i.e. the OSM street network) / modes: TRANSPORT, WALK (for public transport combined with walking) or WALK (for walking accessibility alone – see below) / date: this was set case by case, choosing the most optimal for each timetable GTFS file found for the targeted city.

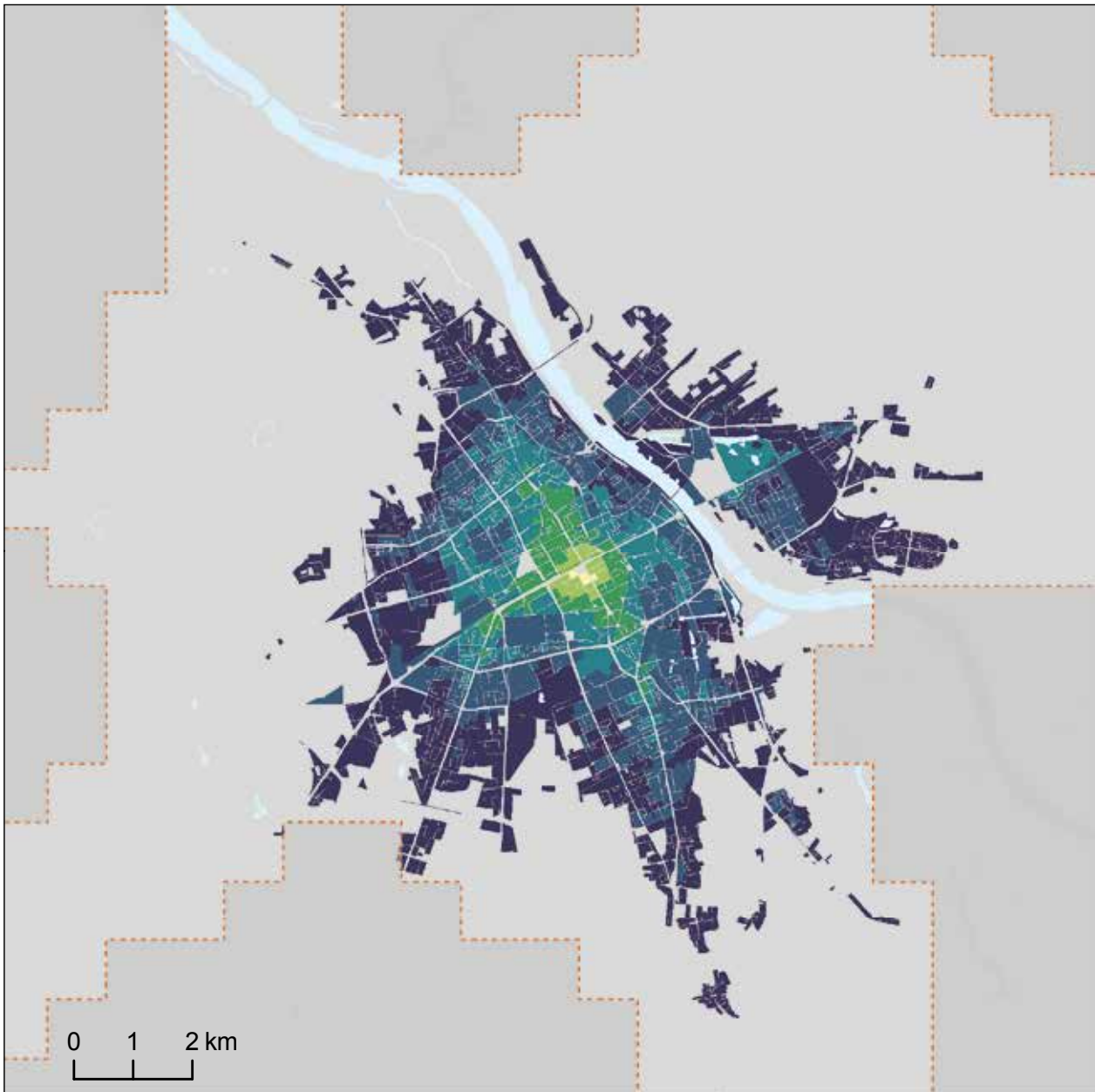
⁴² The origin-destination calculations were scripted in Python. The script input is 1 csv file containing the origins and 1 csv file containing the destinations. The script output is a table with 1 line per origin/destination calculation, containing: origin, destination, requested_time, departure_time, arrival_time, trip_time, total_time, num_boardings, where total_time = trip_time + initial_waiting_time.

The results were aggregated as follows: first, for each origin-destination pair, the average of the total travel time observed from the nine calculations was computed.

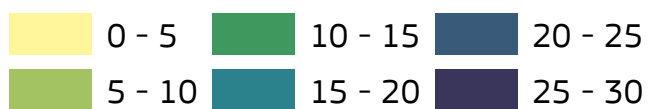
Next, we selected only those origin-destination pairs where the average total travel time was less or equal to the chosen maximum travel time. In our analysis, we applied maxima of 30 and 45 minutes for public transport combined with walking.

Hence, for each origin, the table containing the selected origin-destination pairs lists the destinations that can be reached within the chosen travel time limit, taking into account the frequency and speed of the services. Map 9 illustrates the travel times by public transport starting from the city centre of Warsaw. Such information is obtained for all populated polygons in the urban centre.

MAP 9: Warsaw: travel time from the city centre by public transport



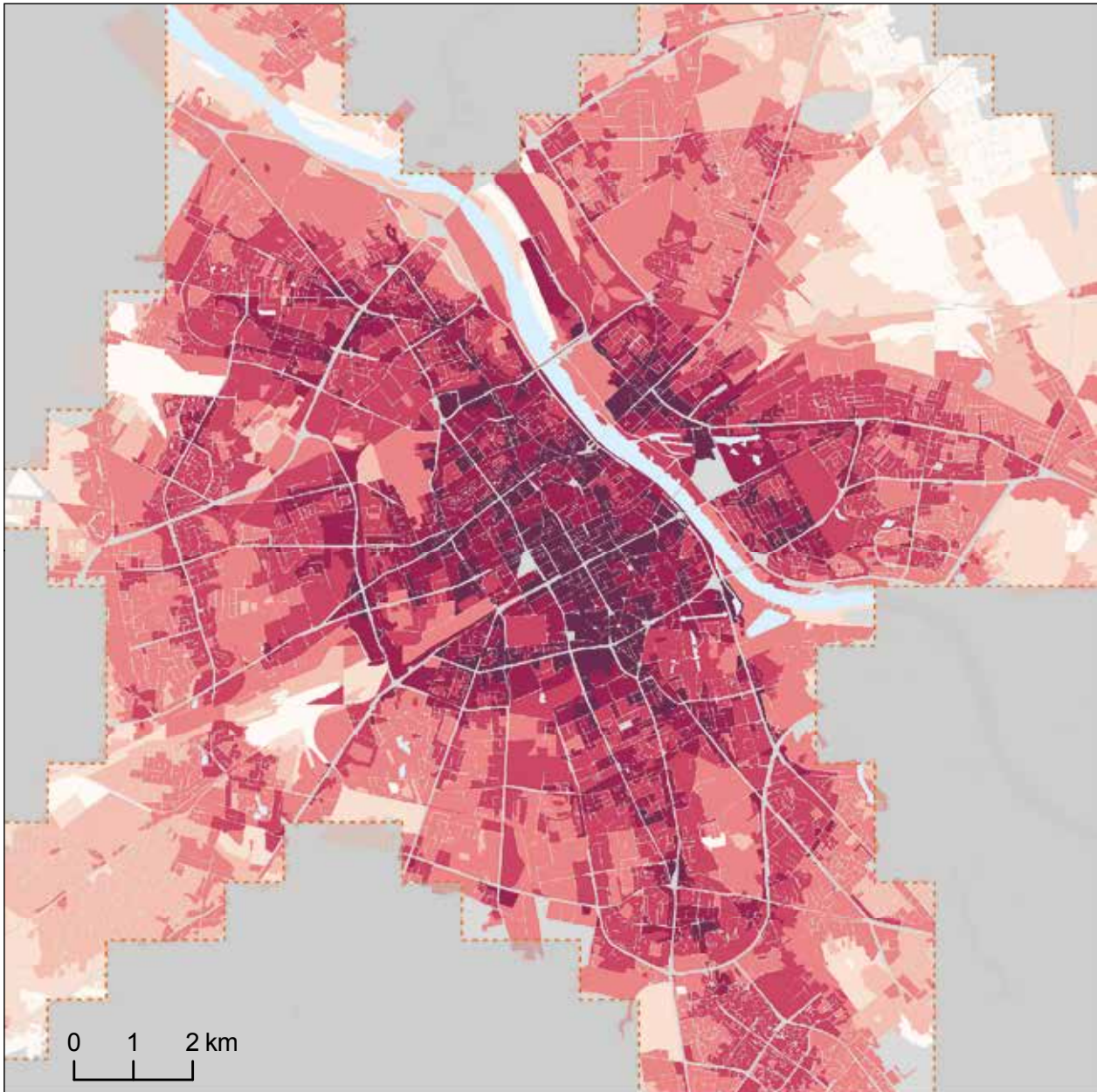
Travel time from the city centre by public transport (minutes)



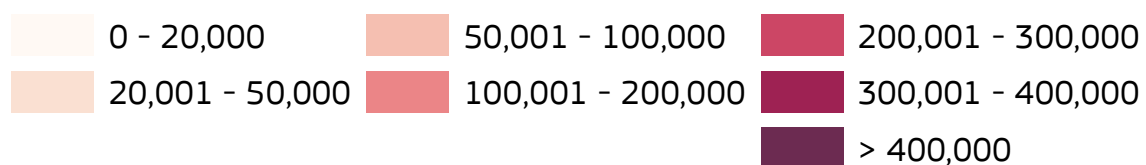
As we know the population at each destination point, further aggregation by point of origin provides the sum of the accessible population. By joining the resulting table to the initial Urban Atlas polygons, the accessible population by polygon of origin can be mapped. For instance, map 10 shows the population

accessible within 30 minutes by public transport (combined with walking) for each of the polygons in the urban centre. Because the analysis is constrained by the boundaries of the urban centre, the absolute accessibility figures for each place of origin are influenced by the urban centre's total population.

MAP 10: Warsaw: population accessible within 30 minutes by public transport



Population accessible within 30 minutes by public transport



At the level of an entire urban centre, an indicator of (absolute) accessibility can be computed, being the weighted average (over all polygons of origin OR) of the accessible population AccP:

We used the same weighted aggregation mechanism for indicators of population proximity and transport performance (see below). If required, population-weighted averages by neighbourhood inside the urban centre could also be produced.

SELECTION OF CITIES

The analysis we designed is computationally very intensive given the large number of origin/destination combinations. Thus, we had to be selective when choosing the cities where we were going to run the computations. We used the following selection criteria:

- ▶ The urban centres of national capitals or of other major cities;
- ▶ Computational feasibility, i.e. size of the urban centre in terms of the number of polygons;
- ▶ Urban centres located in major beneficiary countries of Cohesion Policy support;
- ▶ Availability of workplace-based employment or daytime population estimates by Urban Atlas polygon (see below).

WALKING ACCESSIBILITY

Using the same points of origin and destination, we computed walking time, selecting the destinations which could be reached within 30 minutes of walking. Walking distances were assessed using the OSM street network. Although OSM is not an authoritative data source, we can assume that – at least for the major cities we analysed – the street network data are sufficiently complete to be used to assess walking accessibility.

CYCLING ACCESSIBILITY

While estimating accessibility by bike was, in principle, feasible, it presented additional challenges on the availability and suitability of the input data. To draw a realistic picture of cycling times, we needed a reliable and complete street network dataset with adequate attributes providing information about regulatory and practical constraints and opportunities for cycling. Commercial street networks designed for car-navigation purposes tend to be quite poor in terms of cycling attribute information. Consequently, when using such a network, it is necessary to rely on assumptions derived from the available characteristics of the network segments.

For most of the urban centres, we used the TomTom network combined with the creation of service areas by ESRI ArcGIS. As the TomTom dataset is not really designed for bicycle routing, we selected road segments on the basis of their available attributes⁴³. As a general rule, we allocated a speed of 15 km/h to flat road segments. To pedestrian areas (segments with 'form of way' (FOW) = 14) we applied a speed of 4 km/h. This assumes that cycling is not allowed in these areas or, if it is allowed, the street layout and/or the presence of pedestrians reduce the cycling speed. We applied 10 km/h to walkways (FOW = 15), which were often located through parks. In many cities, contraflow cycling in one-way streets is allowed, at least on part of the network. As the network dataset does not provide information about this rule, we applied the 'bike-friendly' assumption that contraflow cycling would be allowed throughout the network. Finally, we adjusted the speed to the slope of the street. For upward slopes between 3% and 6%, we reduced the speed by 10%; for slopes of 6% or more, we reduced the speed by 20%⁴⁴. Using the travel times per segment, we created service areas of 15 and 30 minutes around the centroids of the populated polygons, and computed the population living (or employed people working) in these areas, constrained by the urban centre boundaries.

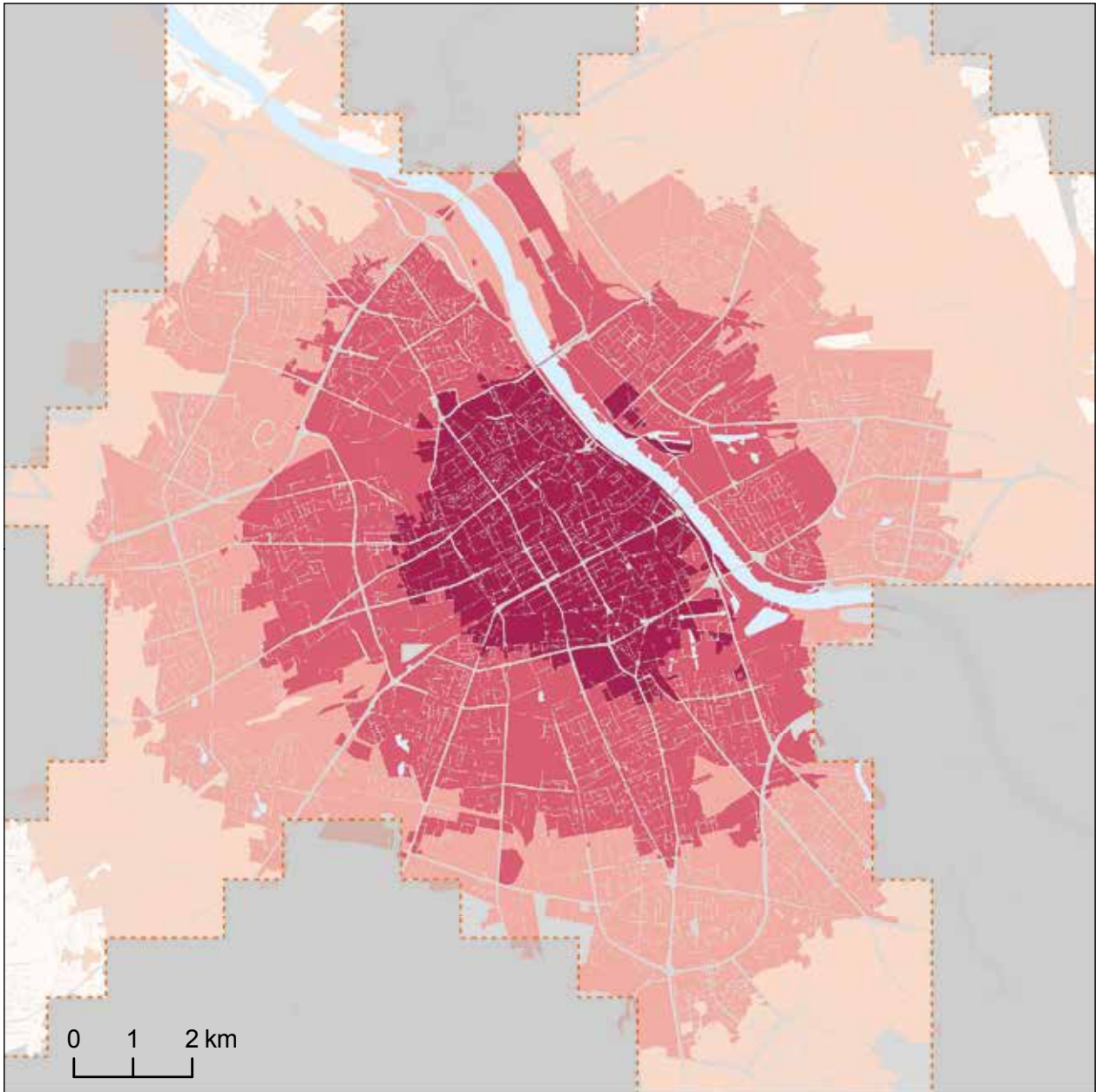
Alternatively, origin/destination computations can be performed using the OTP bike-specific option, which relies on the OSM network. In cities where the OSM network adequately represents the entire street network and provides bike-specific attributes, this may be the best available option⁴⁵. In practice, we used the OTP/OSM combination for the urban centres of Amsterdam, Copenhagen and Ghent. All relevant origin/destination calculations were performed using bike-specific parameters⁴⁶. Destinations within the urban centres that could be reached within 15 or 30 minutes were selected and their population (or employment) summed. Map 11 illustrates the results of accessibility by bike within 30 minutes.

⁴³ All road segments except functional road class (FRC) 0 (= motorways) and excluding FOW 1, 7 and 19 (part of motorway, parking garage and stairs). This selection results in a reasonable approximation of the network available to cyclists, although it cannot be guaranteed that all roads in the selection are actually accessible for cycling.

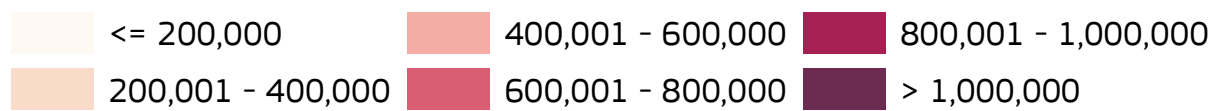
⁴⁴ The slope is obtained from the segment length and the difference in elevation between the start of the segment and its end. As a digital elevation model, we used the Copernicus EU-DEM at 25 m horizontal resolution.

⁴⁵ For instance, the official cycling route planner for the city of Copenhagen uses OSM whereby it is explicitly mentioned that this dataset has been enriched with all the necessary attributes portraying the regulatory constraints and exceptions applying to cyclists.

⁴⁶ The speed was set at 14.9 km/h (4.16 m/s). OTP does not foresee any additional parameters concerning slope adjustment, unless OSM is combined with a digital elevation model. We did not use such a combination because we only applied the OTP process to mainly flat cities.

MAP 11: Warsaw: population accessible within 30 minutes by bike

Population accessible within 30 minutes by bike



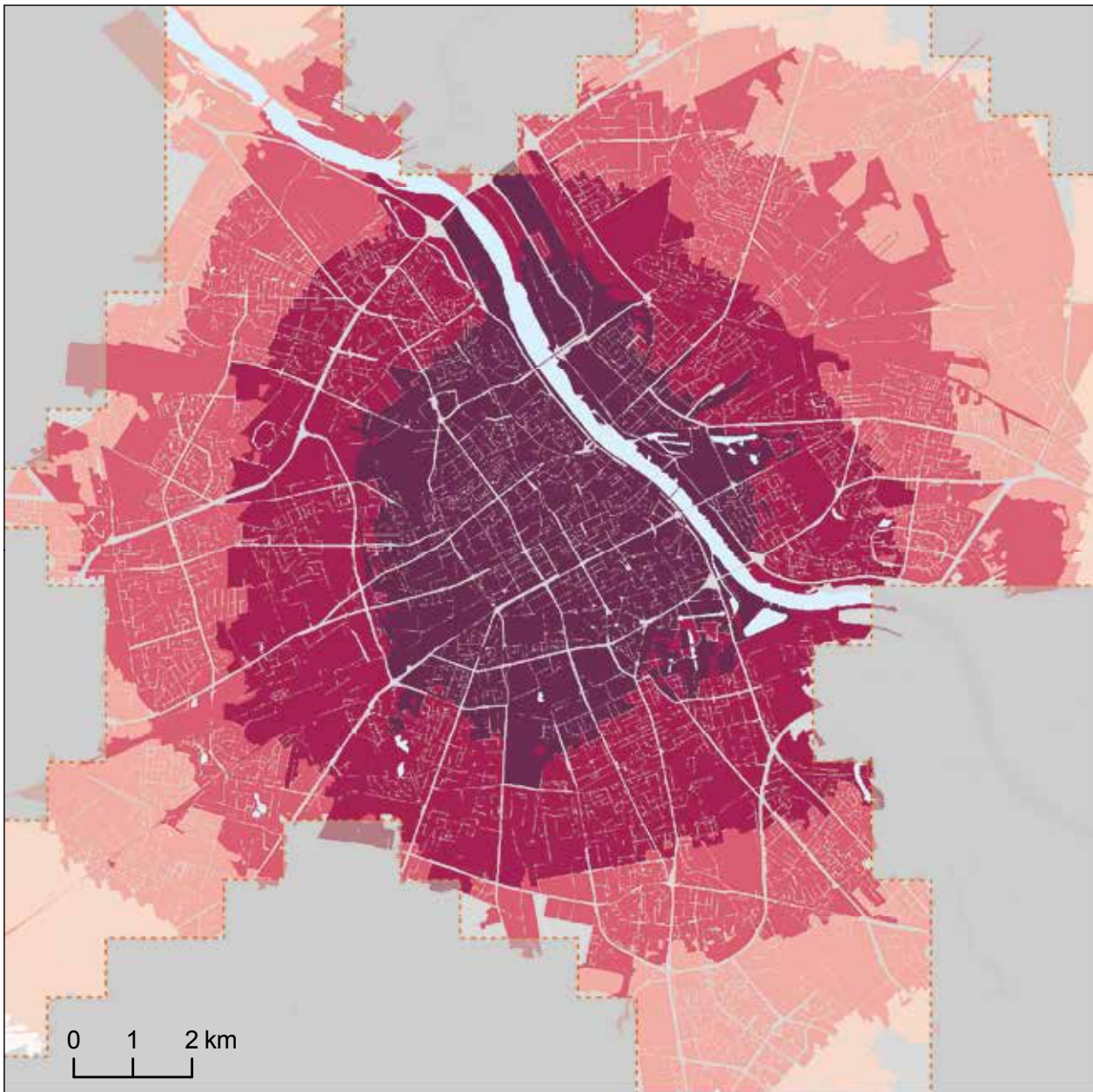
COMPUTING TRANSPORT PERFORMANCE

Initially, the accessibility metrics were expressed in absolute numbers of inhabitants (or of people employed). These figures were influenced by the spatial distribution and concentration of population in the neighbourhood of the departure areas.

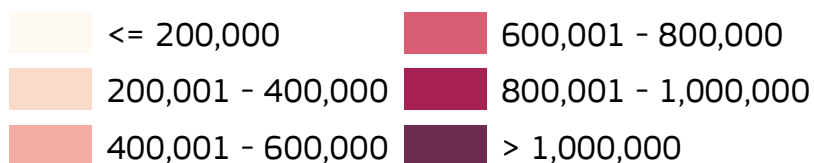
To overcome this limitation, for each departure area, we also computed the number of inhabitants (or people employed) within a straight-line distance of x km around the departure

area. This was achieved by creating polygon buffers around the departure areas and summing the population found within each buffer area. The results of this computation were constrained by the limits of the urban centre, i.e. the neighbouring area under consideration could not exceed the urban-centre boundaries. At the level of the entire urban centre, we computed population-weighted averages of the population found in the neighbourhood of the departure areas. The proximity of population within a 7.5-km radius is illustrated in map 12.

MAP 12: Warsaw: population within a 7.5-km radius



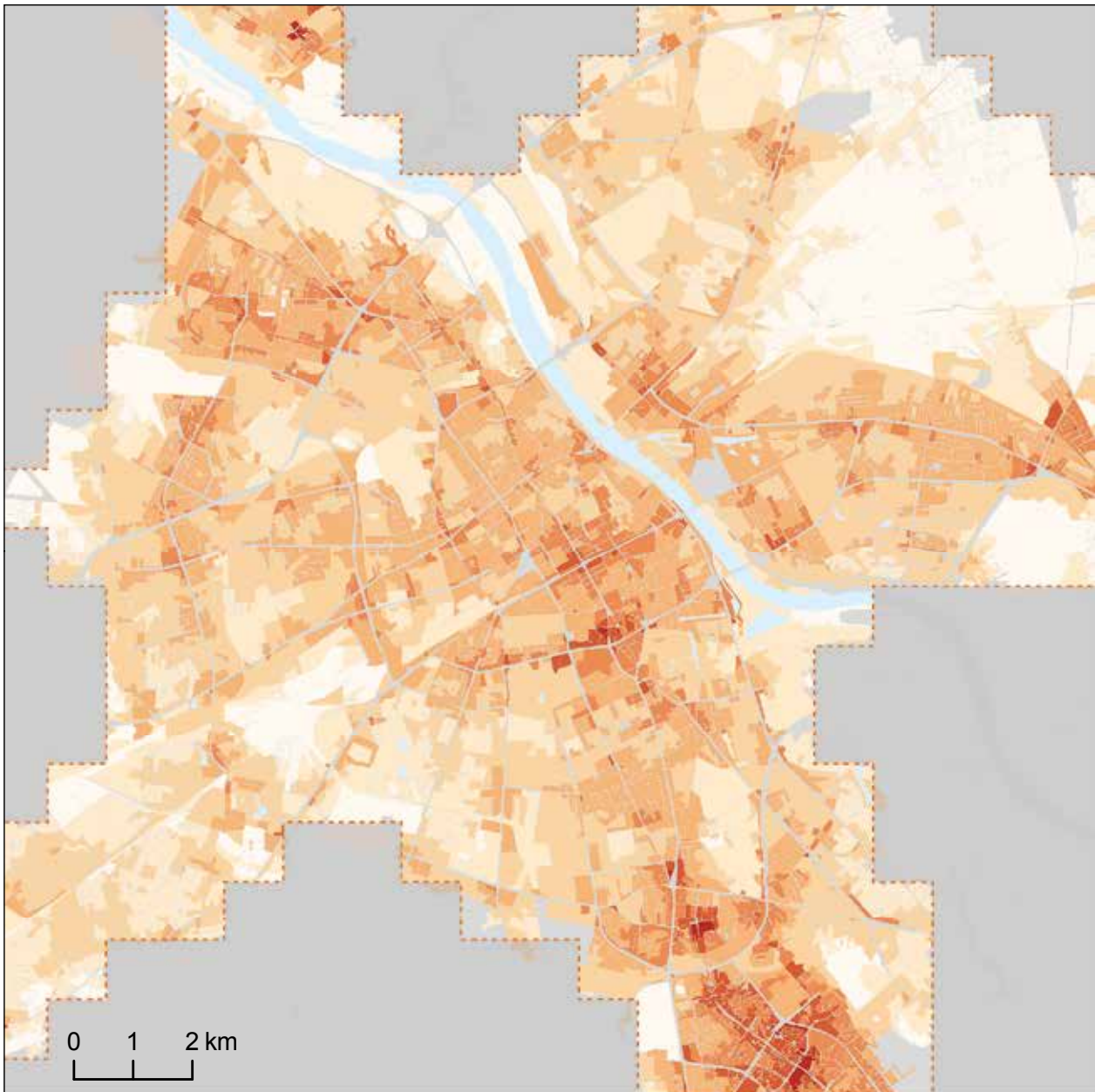
Proximity: population within a 7.5-km radius



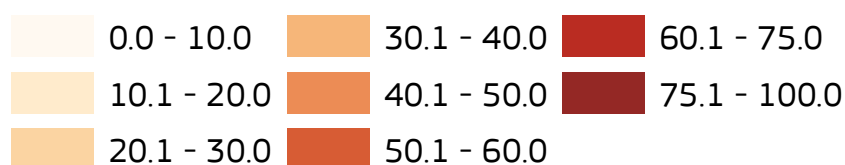
We were then able to express transport performance as the (absolute) accessibility by transport mode divided by the population living in the neighbourhood, multiplied by 100. Public transport and cycling trips lasting a maximum of 30 minutes were compared with the population living within 7.5 km, i.e. corresponding with a straight-line speed of 15 km/h (see map 13 for an example of public-transport performance within 30

minutes of travel time). Public transport trips lasting a maximum of 45 minutes were compared to the population living within 11.25 km. Walking accessibility within 30 minutes was compared to the population in an area covering a 2.5 km radius. Alternatively, accessibility using cycling trips lasting a maximum of 15 minutes could be compared to the population within 3.75 km.

MAP 13: Warsaw: public transport performance for trips within 30 minutes



Public transport performance (30 minutes)



SPEED AND VEHICLE KM TRAVELLED BY PUBLIC TRANSPORT

The timetable data used for the accessibility calculations could also be used to compute estimates of average vehicle speed and the length of all trips made by these vehicles. In this context, distance and speed were measured along straight lines connecting one public transport stop to the next. This limitation is due to the fact that many of the available GTFS datasets do not contain the actual network layout, the only georeferenced data being the XY coordinates of the stops.

From the GTFS feeds, we needed the 'stops' and 'stop_times' tables. First, we ensured we had a dataset of stops in which the coordinates were expressed in metres⁴⁷; only stops located in urban centres were kept in the selection. The stop_times table contains all departure and arrival times at each of the stops as well as the route_type (i.e. the transport mode), trip_id and service_id (this enables a selection of stop times related to services active on a selected weekday). To facilitate further calculations, all time values were converted into decimal numbers.

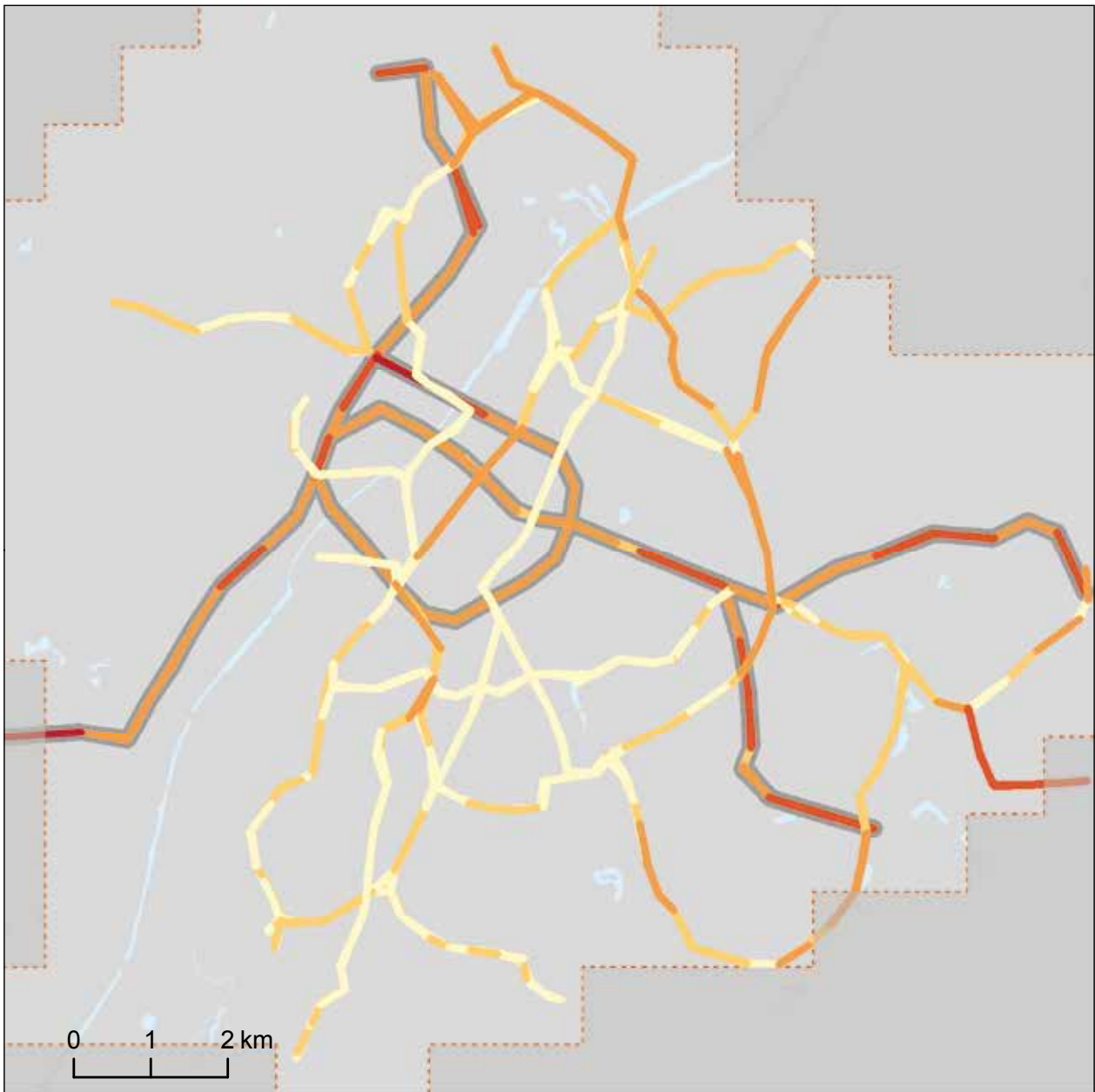
For each of the urban centres, we created two stop time selections: 1) all departures occurring between 6:00 and 20:00 on a chosen weekday; and 2) all arrivals occurring after 6:00 on the same weekday. Then we combined the departure and arrival information. For each departure from a stop the arrival time at the next stop of the trip was queried (providing that this arrival stop was located in the same urban centre). For this selection, it was crucial that the stop_times table contained valid data on the sequence of the stops within each trip. Several GTFS datasets provided incomplete or inconsistent stop sequences⁴⁸ requiring case corrections and gap filling during the GTFS validation process.

The selection of individual sequences of each trip in the urban centre was then combined with information from the stop point features. We had already included the stops' unique identifiers. Then we added the XY coordinates of the departure and arrival stops to each segment which allowed us to calculate the Euclidian distance between each of the subsequent pairs of stops. By dividing this distance by the travel time retrieved from the timetables, we obtained an estimate of the straight-line speed in each segment. Map 14 shows the results for the tram and metro networks in Brussels.

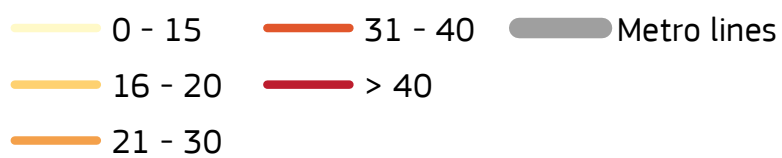
⁴⁷ Initially, the GTFS stops table contained latitude/longitude coordinates in decimal degrees (in WGS84). These were converted to point features and projected to the European equal-area projection (LAEA – EPSG:3035) with units in metres.

⁴⁸ For instance: all stop sequences of a trip were zero or missing, or the series of stop sequences contained gaps.

MAP 14: Brussels: straight-line speed of tram and metro



Straight-line speed of tram and metro (km/h)



Thus, the data were ready for aggregation by urban centre and transport mode: all travel times and Euclidian distances were summed by transport mode and urban centre. From these sums, the average straight-line speed by mode and urban centre was calculated. The sum of vehicle kilometres travelled (for departures between 6:00 and 20:00) could also be expressed relative to the urban centre population.

ESTIMATING EMPLOYMENT FIGURES BY URBAN ATLAS POLYGON

Extending the accessibility analysis to employment required workplace-based employment estimates by Urban Atlas polygons. Ideally, if adequate administrative sources were available to provide employment counts by georeferenced address points, figures on the number of employed by Urban Atlas polygon could have been aggregated. Currently, such a situation proved rather exceptional. Using an earlier version of Copernicus Urban Atlas data (2006), we were able to process address-based employment data for urban centres in Finland, although this required an ad-hoc production of aggregated data by Statistics Finland⁴⁹.

Alternatively, employment data could be estimated at the level of Urban Atlas polygons by means of a disaggregation of data available at the level of larger geographical units or by converting data from another high-resolution geometry such as a grid. These processes can only be successful if adequate ancillary data are available to feed the disaggregation or conversion process. The availability of such data varies among countries, regions and territories. Consequently, the disaggregation or conversion workflow needs to be adapted to different situations. Here, we briefly describe the data combinations we used for cities for which we found workplace-based employment data or daytime population figures.

The Madrid region provides workplace-based employment figures by 'sección'⁵⁰. These units are particularly small in urban areas⁵¹ and are a good starting point for disaggregation towards Urban Atlas polygons. The Spanish Cadastre publishes geodata on buildings and building parts⁵². From these datasets we used a classification of building functions combined with estimates of the volume of the buildings. Each building part has

its surface and comes with data on the number of floors. By multiplying building part area by the number of floors we were able to get an estimate of the total available floor area. These figures were aggregated by building. To each building's floor area we applied a weighting based on the buildings' use category. This weighting represents the probability that the building hosts workplace-based employment. Next, the weighted floor areas were summed by sección and used as a distribution key to spread the employment of the input area across the buildings. Finally, the employment estimates by building were summed by Urban Atlas polygon⁵³.

For the Netherlands and Belgium, we accessed employment data at the sub-local level⁵⁴. The size of these areas varies throughout the countries but provides a decent spatial breakdown in the major cities. We used a disaggregation process similar to that for Madrid, combining data on the function of buildings and their volume⁵⁵ with the Copernicus Urban Atlas land-use/cover classification.

In France, local employment data are available by sector of activity⁵⁶. In Paris, Lyon and Marseille, these data are also broken down by 'arrondissement municipal', i.e. below municipal level. Here again the volume of buildings is used as a key variable to disaggregate the employment figures. The building datasets⁵⁷ come with a classification distinguishing various classes of 'remarkable buildings' (only a relatively small number in comparison to the total number of buildings) and allows for a more interesting distinction between industrial and 'other' buildings. The residual class of 'other' buildings can still include a wide variety of functions. For that reason, we also used the Urban Atlas land-use/land-cover class as a criterion to weight the importance of building volumes. As the employment data are broken down into five sectors of activity (agriculture, industry, construction, market services and non-market services) we were able to adapt the weighting schemes to each of the sectors. We disaggregated each of the sectoral employment datasets separately and finally summed all estimates by Urban Atlas polygon.

⁴⁹ Workplace-based employment data (with reference year 2012) were aggregated by Urban Atlas polygon (2006). Urban Atlas 2012 was not available when the employment aggregation exercise was performed.

⁵⁰ Directorio de unidades de actividad económica – Ocupados (trabajadores) por Sección: <http://www.madrid.org/iestadis/fijas/estructu/economicas/ocupacion/idae10.htm>

⁵¹ The city of Madrid covers 2408 secciones.

⁵² <http://www.catastro.meh.es/webinspire/index.html>

⁵³ The workflow used for Madrid is described in more detail in a technical note: Poelman (2016).

⁵⁴ Netherlands: by four-digit post code area: LISA Landelijk Systeem van Arbeidsplaatsen: www.lisa.nl

Belgium: by statistical sector: <https://statbel.fgov.be/fr/open-data/census-2011-matrice-des-deplacements-domicile-travail-par-secteur-statistique>

⁵⁵ '3D Gebouwhoogte NL' layer of the Dutch Cadastre: <https://www.pdok.nl/>

'3D GRB' layer of the Flemish Regional Government: https://download.vlaanderen.be/Producten/Detail?id=971&title=3D_GRB and building footprints for Brussels: <https://cirb.brussels/fr/nos-solutions/urbis-solutions/urbis-data/urbis-adm>

⁵⁶ INSEE CLAP data (Connaissance locale de l'appareil productif): <https://www.insee.fr/fr/metadonnees/source/serie/s1162>

⁵⁷ IGN-F 'BD TOPO thème bâtiments': http://professionnels.ign.fr/sites/default/files/DL_vecteur.pdf

ESTIMATING DAYTIME POPULATION BY URBAN ATLAS POLYGON

Data on the spatial distribution of daytime population are not commonly available for European cities. Computing daytime population typically requires adequate georeferenced census data, combinations or various register-based datasets or modelling based on big data such as spatio-temporal distributions of mobile phone data. Below, we illustrate a few cases where input data on daytime population are available.

Ireland produced census results for 2016 on the number of workplace-based employed and daytime population by small 'workplace zone'⁵⁸. We computed estimates of employment and daytime population by Urban Atlas polygon for the urban centre of Dublin. The disaggregation process was steered by the volume of the buildings weighted according to their location in Urban Atlas classes. We estimated the volume of the buildings by multiplying the built-up intensity from the European Settlement Map 2017 by the building height from the Copernicus Urban Atlas digital surface model, both at 10 x 10 m grid-cell resolution⁵⁹. The weights by land-cover/land-use class, attached to the estimated building volumes, were adapted to the downscaling of daytime population and employment. This means that, in comparison to downscaling the residential population, more weight is given to non-residential urban land-use classes. For the other urban centres in Ireland (Cork and Limerick), Copernicus building-height data were not available. In these areas, the disaggregation process used building surface instead of volume, again combined with the land-cover/land-use class. To partly compensate for the absence of building height information, we used different weights to disaggregate employment in agriculture, industry and services.

Statistics Estonia has produced a 1 km² grid of estimated daytime population, combining sample census data for 2016 with information about workplaces and schools⁶⁰. This provides useful input data for a disaggregation process computing estimates of daytime population by Urban Atlas polygon. As in the case of Ireland, we assumed that the distribution of the grid-based daytime population by Urban Atlas polygon is a function of building location, land use and building height. Again, the estimation process followed two major steps. First, we downscaled the population figures to the level of built-up grid cells. Secondly, the estimates at built-up grid-cell level were aggregated (summed) by Urban Atlas polygon. In the first step, we divided the grid-based daytime population by building, using the volume of the building weighted in accordance to the land-use category of the place where the building is located. The Urban Atlas building height dataset only covers the city of Tallinn and its urban centre (high-density cluster). Consequently, the spatial scope of this analysis is the combined extent of the city and the urban centre of Tallinn.

⁵⁸. <https://www.cso.ie/en/census/census2016reports/workplacezonesand1kmpopulationgrids/>

⁵⁹. JRC ESM European Settlement Map: <https://ec.europa.eu/jrc/en/publication/european-settlement-map-2017-release-methodology-and-output-european-settlement-map-esm2p5m> and Copernicus Urban Atlas DSM building height layer: <https://land.copernicus.eu/local/urban-atlas/building-height-2012>

⁶⁰. Statistics Estonia (2018): <https://estat.stat.ee/StatistikaKaart/VKR>

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ACKNOWLEDGMENTS

This paper and analysis were only possible thanks to the help and advice from many people. In particular, we would like to thank Emile Robe and Olivier Draily for their never-ending efforts in converting and validating timetable data and for the development and implementation of tools for evaluating access to public transport, proximity and cycling accessibility. Thanks also to Filipe Batista (JRC) for the successful development of the process of disaggregation of population data to Urban Atlas polygons. Philip Turner from UITP⁶¹ volunteered to promote open public transport timetable data dissemination amongst the UITP members. And finally, we would like to thank all those public transport operators and mobility data integrators for their efforts to provide open data.

⁶¹ UITP: Union Internationale des Transports Publics – International Association of Public Transport.

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Editor: Lewis Dijkstra, European Commission, Regional policy
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doi:10.2776/021137
ISBN 978-92-76-10253-3