PROSPECTIVE

Transport Connectivity

Final Report

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PROSPECTIVE

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This report was commissioned as part of the evidence base for the National Infrastructure Assessment. The views expressed and recommendations set out in this report are the authors' own and do not necessarily reflect the position of the National Infrastructure Commission.

Executive Summary

This report proposes a methodology for developing transport performance indicators to indicate transport connectivity and presents the results of its implementation in the UK. The work is aiming to strengthen the Commission's ability to make objective and evidence-based policy recommendations on the priorities for transport investment.

The indicators are organised in three different spatial levels:

1. Within cities: this provides connectivity metrics for each city in Great Britain, as measured by the speed of travel by private or public transport between each point in the city and its centre.

2. Between cities and other locations: this provides connectivity metrics for each built-up area in Great Britain, as measured by the speed of travel by private or public transport between its centre and any other point in Great Britain.

3. Between cities and international destinations: this provides connectivity metrics for each city in Great Britain, as measured by the speed of travel by private or public transport between its centre and cities in the rest of the world.

We use observed data, state-of-the-art transport modelling and economic theory to derive these indicators. For each city centre we calculate two sets of indicators for each transport mode and demand type: accessibility (primary indicator) and attractiveness (supplementary indicator). Each of these sets includes connectivity indicators for (i) private transport off-peak time, (ii) private transport peak time, (iii) public transport (including bus, coach and rail) and (iv) the minimum travel time across all transport modes. All connectivity indicators are developed for 2011 and 2016.

We represent demand at each destination, either by resident population or workplace employment. The aim is to provide proxy metrics for both domestic final demand and intermediate demand that balance the requirement for UK-wide, high-level assessment with full consideration of the spatial distribution of demand for goods and services.

To calculate travel times for each transport mode collection, we use a multimodal transport network, which provides end-to-end (from location of demand to arrival to city centre) travel times both for free flow time and peak time travel speeds (for private transport) and takes into account walking and waiting time (based on service frequency) for public transport.

All indicators are normalised by as-the-crow-flies equivalent metrics. The normalised indicators represent the effectiveness of a transport mode in facilitating access to demand from a city centre after the physical proximity to the locations of demand has been accounted for. As such, they represent the effectiveness of the transport infrastructure in serving the demand-supply system considering its distribution in space.

Following the definition of our connectivity indicators, we can map the contribution of each demand location in the accessibility of each city. The results of our analysis suggest that by aggregating connectivity contributions at the level of Primary Urban Areas (as defined by the Centre for Cities), we can discover strong and weak inter-urban connectivity and infrastructure relationships that highlight the performance of the transport network.

1. Introduction

One of the key mechanisms through which infrastructure services can affect economic growth, competitiveness and quality of life is through improvements in transport networks. As discussed by the National Infrastructure Commission in its paper focused on economic growth (NIC 2017), transport connectivity may directly increase productivity, lower costs for firms, improve access to supply chains, enable exports and deliver agglomeration economies. In addition, transport services allow people to access work, education and health services, leisure, family and community which matters for quality of life.

Transport connectivity is understood by the Commission to represent the effectiveness of the transport network (irrespective of mode) at getting people from one location to another. This in turn will depend on the time within which a number of individuals can reach different destinations via the transport network.

This report proposes a methodology for developing transport performance indicators to indicate transport connectivity and presents the results of its implementation in the UK. The work is aiming to strengthen the Commission's ability to make objective and evidence-based policy recommendations on the priorities for transport investment. It is expected that the indicators will be used to inform the assessment of the performance of inter-city and intra-city transport, and recommendations relating to this.

2. Methodology

The report presents a methodology for constructing transport connectivity metrics, based on a sound theoretical framework, and the results of quantifying current and historic connectivity as per these metrics' definitions.

The proposed metrics are organised in three different spatial levels:

1. Within cities: this provides connectivity metrics for each city in Great Britain, as measured by the speed of travel by private or public transport between each point in the city and its centre, weighted by demand in each point. The main unit of analysis corresponding to cities is Primary Urban Area (PUA), as per the Centre for Cities' definition (2016), which includes 63 cities.

2. Between cities and other locations: this provides connectivity metrics for each built-up area in Great Britain, as measured by the speed of travel by private or public transport between its centre and any other point in Great Britain, weighted by demand in each point. The main unit of analysis corresponding to built-up areas is the 1000 Built-Up Areas (BUA) with the highest population according to the 2001 Census, as per the ONS/NRS definition.

3. Between cities and international destinations: this provides connectivity metrics for each city in Great Britain, as measured by the speed of travel by private or public transport between its centre and cities in the rest of the world, weighted by demand in the international destinations. At the international level the study focuses on the international destinations and modes of travel which should be included in the metric and the method of their allocation.

The proposed connectivity indicators can be used to provide a meaningful assessment of the performance of UK's inter-city and intra-city transport networks. They are designed to allow the Commission to identify current pressures on the transport network, and to pick up constraints based on the transport network itself (i.e. places that have poor connectivity because their most direct transport links are poor) as well as capacity issues (i.e. speeds between certain places are low because of congestion).

The implementation of the proposed methodology for the calculation of 'Between cities and international destinations' connectivity indicators is beyond the scope of this project. As such the proposed methodology is presented in section 2.4 (supplementary connectivity indicators) with a view of being used in the future to generate such indicators.

2.1 Key principles

This report contains a descriptive analysis of the three sets of connectivity indicators constructed, a detailed description of the methodology used to calculate them and the theoretical justification. The approach to producing the connectivity indicators is based on the following priorities:

2.1.1 Consistency

We use a consistent approach grounded in contemporary spatial interaction theory and transport demand analysis to construct indicators at all three spatial levels. For all three spatial levels we use the same transport network, definitions of demand and methodology to generate the connectivity metrics.

2.1.2 Robustness

We use observed data, state-of-the-art transport modelling and economic theory to derive meaningful indicators. For each city we calculate two sets of indicators for each transport mode and demand type: accessibility (primary indicator) and attractiveness (supplementary indicator).

2.1.3 Comprehensiveness

Following the authority's statement of requirements, we generate primary and supplementary sets of indicators for each of the three target spatial levels.

Each of these sets includes connectivity indicators for (i) private transport off-peak time, (ii) private transport peak time, (iii) public transport (including bus, coach and rail) and (iv) the minimum travel time across all transport modes.

2.1.4 Comparability and future proofing

All connectivity indicators are developed for 2011 and 2016. Details on data sources for both years is provided in Appendix 3.

Moreover, the developed method is extensible and can be run in the future with minimal effort; i.e. is based on input data that are updated regularly and the process of calculating the indicators from these inputs is sufficiently automated.

2.2. Defining cities and their centres

To produce connectivity metrics for cities across Great Britain we require a predefined set of cities, and a method for defining their boundaries and their city centres.

2.2.1 Cities

To generate a set of cities for England and Wales we use the Office for National Statistics 2011 Built-up Areas dataset (Office for National Statistics 2013). Equivalently, for Scotland we use the National Records of Scotland Settlements (Urban Areas) in Scotland dataset, published by Scottish Government Spatial Data Infrastructure in 2014.

Moreover, each of the 63 Primary Urban Areas, defined by the Centre for Cities, has been manually matched to a ONS/NRS Built-Up Area. The results of the matching process are presented in Appendix 5.

2.2.2 City centres

We define the city centre of each Built-Up Area (BUA) as a set of locations where commercial activity is exceptionally intense. In particular, for each BUA, we define as city centre, the set of 2011 Census Output Areas (OAs) which present the highest job density expressed as:

$$\textit{centrality score} = \textit{workplace employment within } 15 \textit{ minutes walk from the OA}$$

Appendices 1 and 2 detail the methodology used to define Built-Up Areas (BUA) and city centres across the UK.

2.3. Primary connectivity indicators

2.3.1. Defining connectivity for each of the three target spatial levels

For the “within cities” (**intra**) set of indicators we calculate the connectivity of the city centre of a Primary Urban Area (PUA) as its connectivity (by transport mode) to all destinations within the boundaries of the PUA weighted by demand and distance.

For the “between cities and other locations” (**inter**) set of indicators we calculate the connectivity of the city centre of a BUA as its connectivity (by transport mode) to all other destinations across the UK (destinations outside the BUA’s boundary) weighted by demand and distance.

We also provide a simple (**total**) indicator for which we calculate the connectivity of the city centre of a PUA/BUA as its connectivity (by transport mode) to all other destinations across the UK weighted by demand and distance.

2.3.2 Using accessibility to measure connectivity

For each city centre i we calculate a set of intra-urban and inter-urban key metrics (primary/accessibility indicators) for each transport mode m and demand type p which represent the *accessibility* of each city centre to demand for p:

$$U_{im,p} = \sum_{j} w_{j,p} \times exp(-\beta_p \times t_{ijm})$$

where, $w_{j,p}$ is the level of demand of type p in destination j, t_{ijm} is the travel time from city centre i to destination j using transport mode m and β_p represents that impact of distance/travel time on the attractiveness of city centre i to consumers in j. Please see Appendix 6 for details on setting values for β_p and the results of a sensitivity analysis.

The accessibility metric resembles Harris’ original formulation (Harris 1954, Krugman 1992), weighting demand at each destination by the distance to this destination from the city centre. It is equivalent to Hansen’s accessibility measure (1959), originally proposed by Stewart (1941) and first applied to the continental USA by Warntz (1959) to explain spatial price differentials. The team (Prospective and CASA) have extensive expertise in developing such measures.

The metric reflects how accessible demand for p is from city centre i. As such, it represents how easy it is for economic activity in city centre i to reach locations of demand (markets).

2.3.3 Indicators by transport mode and time of day

We produce accessibility metrics for a set of transport modes and times of day, including (i) private transport off-peak time, (ii) private transport peak time, (iii) public transport (including bus, coach and rail) and (iv) the minimum travel time across all transport modes $min_m(t_{ijm})$ where t_{ijm} is the travel time from i to j using transport mode m.

While calculating the accessibility metrics we are also outputting the amount of demand within time from each time centre for each mode; e.g. how much demand can be reached within 20 minutes, when travelling by public transport.

2.3.4 Normalisation

All above indicators are normalised by as-the-crow-flies equivalent metrics:

$$U'_{i,p} = \sum_j w_{j,p} \times exp(-\beta_p \times d_{ij})$$

The final normalised accessibility indicators $W_{im,p}$ represent the effectiveness of transport mode m in facilitating access to demand p from city centre i after the physical proximity (Euclidean distance) to the locations of demand has been accounted for.

$$W_{im,p} = U_{im,p}/U'_{i,p}$$

where d_{ij} is the Euclidean distance between i and j. The normalisation process highlights the effectiveness of the transport infrastructure in serving the demand-supply system considering its distribution in space.

2.4. Supplementary connectivity indicators

In addition to the set of primary indicators, we generate a set of supplementary/attractiveness indicators which represent the *attractiveness* of each city centre to demand for p:

$$X_{im,p} = \sum_j w_{j,p} \times \frac{w_{i,p} \times exp(-\beta_p \times t_{ijm})}{\sum_i w_{i,p} \times exp(-\beta_p \times t_{ijm})}$$

where, $w_{i,p}$ is the level of production of type p in city centre i. The attractiveness metric, which is compatible with random utility theory (McFadden 1974), reflects how attractive a city centre i is perceived to be by consumers of p considering their distance to i and competing city centres.

The combined consideration of accessibility and attractiveness metrics provides a robust framework for evaluation. It allows the calculation of the consumer surplus for each city centre following investment in transport as the ratio:

$$CS_{im,p} = \sum_j w_{j,p} \times exp(-\beta_p \times t_{ijm}) / \sum_j w_{j,p} \times exp(-\beta_p \times t'_{ijm})$$

where t'_{ijm} is the travel time from city centre i to destination j using transport mode m after the transport investment. Moreover, with the attractiveness metric, it also directly considers the impact of transport investment on the competition between centres in attracting demand by internalising the elasticities of time travel improvements in attracting demand.

2.4.1 Connectivity to international destinations

For the “between cities and international destinations” indicator we propose the definition of the connectivity (by transport mode) of the city centre of a PUA as its connectivity to all international portals (international airports, train stations and ferry ports) weighted by portal significance (number of passengers) and distance.

In particular, we propose that for each international portal (international airport, train station or ferry port), the resulting connectivity considers the following parameters:

1. The portal’s significance and capacity, measured as the annual number of passengers travelling via this portal to international destinations.

2. The portal's distance to major international destinations that it connects measured in travel time between the portal and the respective international portal at the destination (e.g. travel time from origin airport to destination airport).
3. The estimated GVA served by each of the destination portals that the origin international portal connects.

Parameters 1, 2 and 3 should be combined to represent access to market via an international portal:

$$U_i = w_i \times \sum_j w_j \times exp(-\beta_p \times d_{ij})$$

Where w_i represents international portal's i significance and capacity, w_j represents the estimated GVA served by the destination portal j and d_{ij} is the travel time between the two portals. β_p reflects the relative impact of distance on international travel.

2.5. List of connectivity indicators

In the results section, we present both accessibility and attractiveness indicators for the two focal spatial levels (within cities, between cities and other locations) according to table 2.1.

Table 2.1. List of all outputs by metric, period, transport mode and scope

Metric	Period	Transport mode	Scope
Accessibility	2011	Car peak time	Total
Accessibility	2011	Car off-peak time	Total
Accessibility	2011	Public transport	Total
Accessibility	2011	Minimum travel time	Total
Accessibility	2011	Crow-fly	Total
Accessibility	2011	Car peak time	Intra
Accessibility	2011	Car off-peak time	Intra
Accessibility	2011	Public transport	Intra
Accessibility	2011	Minimum travel time	Intra
Accessibility	2011	Crow-fly	Intra
Accessibility	2011	Car peak time	Inter
Accessibility	2011	Car off-peak time	Inter
Accessibility	2011	Public transport	Inter
Accessibility	2011	Minimum travel time	Inter
Accessibility	2011	Crow-fly	Inter
Attractiveness	2011	Car peak time	Total
Attractiveness	2011	Car off-peak time	Total

Attractiveness	2011	Public transport	Total
Attractiveness	2011	Minimum travel time	Total
Attractiveness	2011	Crow-fly	Total
Attractiveness	2011	Car peak time	Intra
Attractiveness	2011	Car off-peak time	Intra
Attractiveness	2011	Public transport	Intra
Attractiveness	2011	Minimum travel time	Intra
Attractiveness	2011	Crow-fly	Intra
Attractiveness	2011	Car peak time	Inter
Attractiveness	2011	Car off-peak time	Inter
Attractiveness	2011	Public transport	Inter
Attractiveness	2011	Minimum travel time	Inter
Attractiveness	2011	Crow-fly	Inter
Accessibility	2016	Car peak time	Total
Accessibility	2016	Car off-peak time	Total
Accessibility	2016	Public transport	Total
Accessibility	2016	Minimum travel time	Total
Accessibility	2016	Crow-fly	Total
Accessibility	2016	Car peak time	Intra
Accessibility	2016	Car off-peak time	Intra
Accessibility	2016	Public transport	Intra
Accessibility	2016	Minimum travel time	Intra
Accessibility	2016	Crow-fly	Intra
Accessibility	2016	Car peak time	Inter
Accessibility	2016	Car off-peak time	Inter
Accessibility	2016	Public transport	Inter
Accessibility	2016	Minimum travel time	Inter
Accessibility	2016	Crow-fly	Inter
Attractiveness	2016	Car peak time	Total
Attractiveness	2016	Car off-peak time	Total
Attractiveness	2016	Public transport	Total
Attractiveness	2016	Minimum travel time	Total
Attractiveness	2016	Crow-fly	Total

Attractiveness	2016	Car peak time	Intra
Attractiveness	2016	Ca off-peak time	Intra
Attractiveness	2016	Public transport	Intra
Attractiveness	2016	Minimum travel time	Intra
Attractiveness	2016	Crow-fly	Intra
Attractiveness	2016	Car peak time	Inter
Attractiveness	2016	Car off-peak time	Inter
Attractiveness	2016	Public transport	Inter
Attractiveness	2016	Minimum travel time	Inter
Attractiveness	2016	Crow-fly	Inter

2.6. Demand representation

There is a need to weight the connectivity scores between the city centre and any particular destination by the demand in this destination. However, the definition of demand is open to interpretation.

We are implementing two distinct weighting strategies, one based on population and one based on employment. The aim is to provide proxy metrics for both domestic final demand and intermediate demand that balance the requirement for UK-wide, high-level assessment with full consideration of the spatial distribution of demand for goods and services (ONS 2017).

2.6.1. Weighting by residential population

Use the number of residents in each destination as a proxy for domestic final demand. This is based on two assumptions: (i) demand generated via government expenditure and fixed capital formation follows the spatial distribution of the population, and (ii) socio-economic characteristics and household composition are relatively similar for all destinations.

2.6.2. Weighting by jobs

Use the number of jobs in each destination as a proxy for intermediate demand. This is based on two assumptions: (i) the proportion of jobs in each industry sector is constant across space, and (ii) intermediate demand per job in each sector is constant across space.

2.7. Infrastructure representation

To calculate travel times for each transport mode collection, we use a multimodal transport network, which provides end-to-end (from location of demand to arrival to city centre) travel times both for free flow time and estimated peak time travel speeds (for private transport) and takes into account walking and waiting time (based on service frequency) for public transport.

In particular we use a deeply integrated multimodal UK transport network that provides a continuously updated detailed representation of the public transport service provision and road network in the UK.

The used multimodal transport network combines (i) a detailed road network (contains every street segment and path in Great Britain), (ii) a full representation of the bus/coach/tram network (including every bus-stop, route and service in Great Britain), (iii) a full representation of the train/metro network (including every station and service in Great Britain), (iv) a full representation of the ferry network.

These uni-modal networks are combined into a deeply integrated multimodal transport network through direct representation of all transit points (bus-stops, rail stations, ports, car parks etc.).

Further details on Prospective's multimodal transport network can be found in Appendix A4.

2.9. Limitations of the adopted approach

The application of the proposed approach in producing transport connectivity indicators has a number of limitations:

2.9.1. Over-reliance on city centres

The method relies on the identification of city centres for each city and the subsequent use of these city centres as the primary employment locations in each city.

For specific types of analysis (finer spatial level), and particularly in cases where the centre of a city does not function as its sole or major predominant employment location this approach would not be appropriate. In such cases connectivity calculations would require consideration of any employment location within a city. This however would drastically increase the complexity of the calculation of the respective connectivity metrics, deeming this approach unsuitable for nation-wide analysis.

In cases where the consideration of all employment locations in each city is computationally feasible an adopted method should be prefered. This would still use the formulation in section 2.3.2 to calculate the accessibility of each employment location within a city and would aggregate the weighted (by employment size) individual employment centre accessibilities to provide a city-wide metric. Such an approach would ensure that when employment in a city is spatially dispersed or organised in multiple centres its connectivity is not systematically underestimated.

2.9.2. Impact of capacity and travel cost

The proposed approach avoids to translate spatial relationships between demand locations and city centres (as defined by the accessibility and attractiveness indicators) into concrete transport flows (e.g. number of passengers). This level of abstraction is useful for evaluating connectivity potential in principle but fails to consider the impact of network capacity on transport availability.

It is also not sufficient to address questions such as where does the transport infrastructure suffer from bottlenecks and what is their impact on location choice and route/transport mode selection?

Similarly the produced indicators are based solely on travel times and they do not consider monetary aspects of travel costs (parking costs, fares etc.).

3. Results

3.1. Distance profile

In order to produce the proposed connectivity metrics for each city, we must calculate the amount of demand within time from its centre for each mode; e.g. how much demand can be reached within 20 minutes, when travelling by public transport. The resulting “distance profile” of each city is a valuable output in its own.

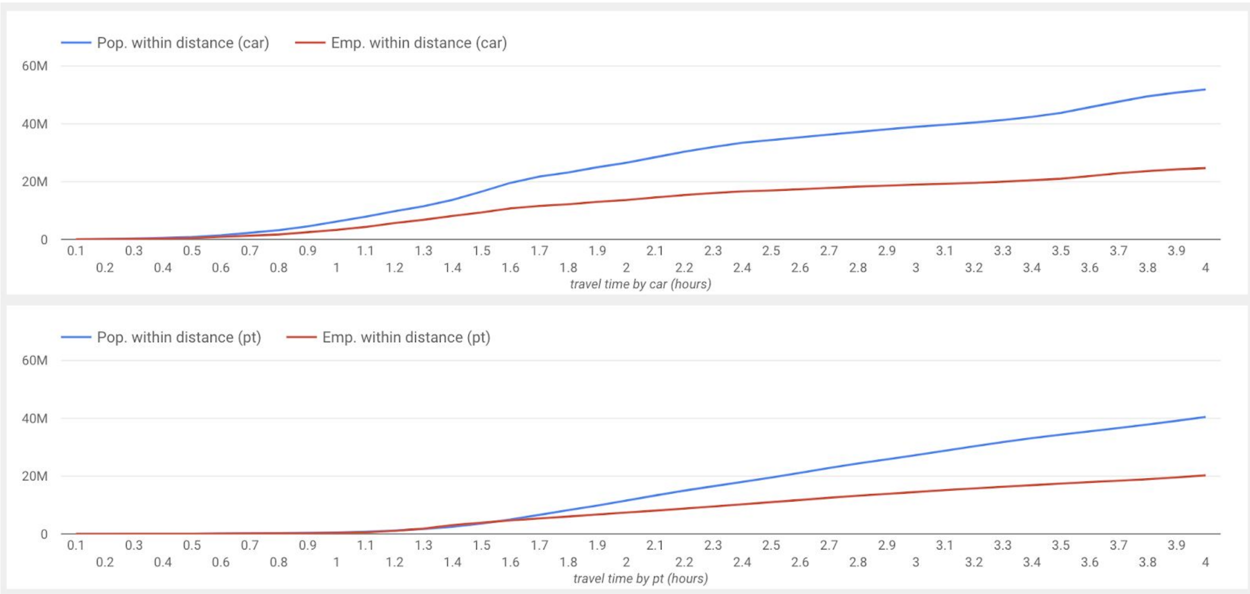


Figure 1. Distance profile analysis for Reading (2016) | top: car, bottom: public transport

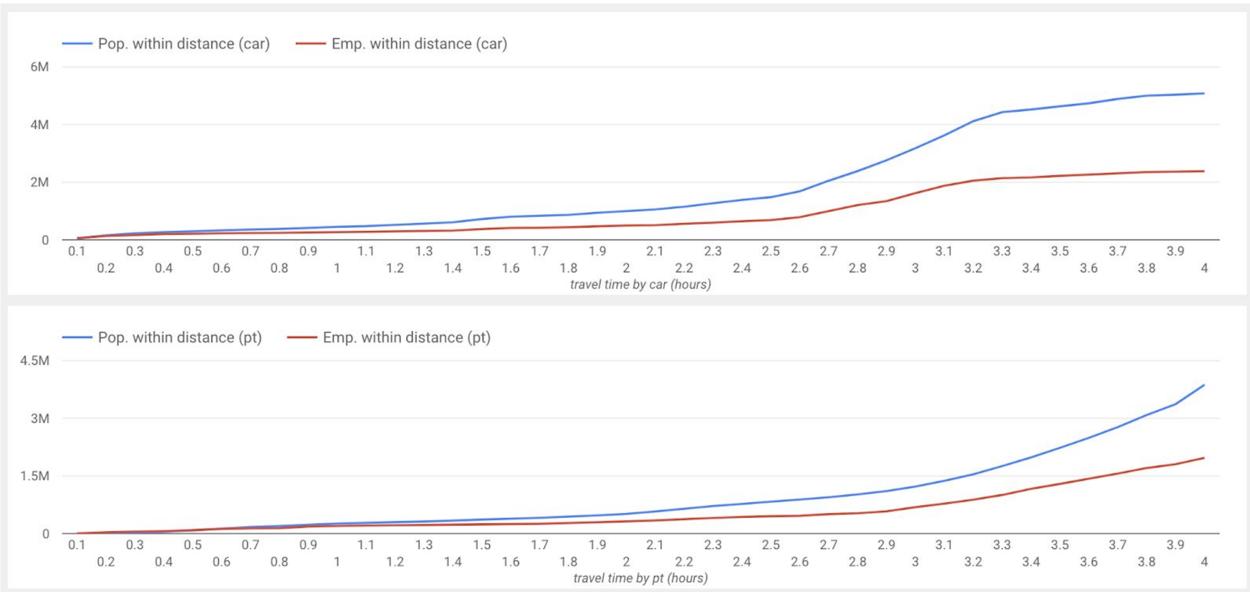


Figure 2. Distance profile analysis for Aberdeen (2016) | top: car, bottom: public transport

In the two examples in this section (figures 1 and 2), in the case of Reading the impact of its proximity to London becomes evident both in the case of car-based and public transport-based profiles by the respective change in the steepness of the population and employment profiles at 45-50 mins (by car) and the 1 hour and 15 mins (by public transport). In the case of Aberdeen the steepness of the profiles changes at 2 hours 30 mins for car and 3 hours for public transport, when Edinburgh and Glasgow are reached by the two transport modes.

3.2. Spatial distribution of accessibility contributions

Following the definition of the accessibility indicator, we can calculate the contribution of each demand location (Census Output Area) in the accessibility of each city:

$$U_{ijm,p} = w_{j,p} \times exp(-\beta_p \times t_{ijm})$$

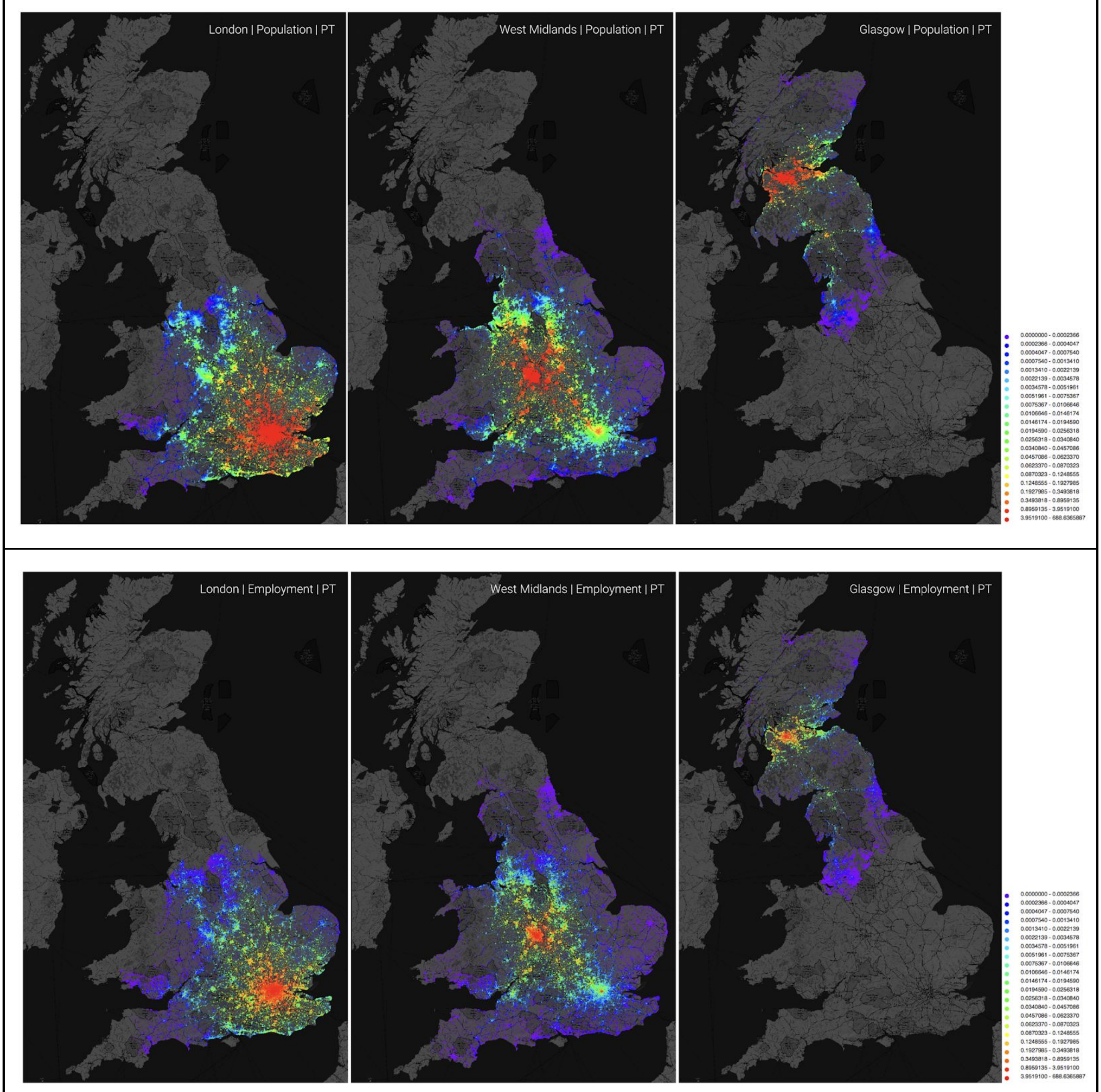


Figure 3. Population-based (top) and employment-based (bottom) public transport accessibility contributions (2016) for the London, West Midlands (Birmingham) and Glasgow PUAs

The maps display the contribution of each OA in the accessibility of different cities. For example in figure 3, the three top/bottom maps (population and employment -based demand respectively) show the contribution that each demand location has on London, Birmingham and Glasgow. As expected based on the equation above, the maps show that demand locations closer to the centres of each of the three cities, and locations with more demand (high population in the top 3 maps and high employment in the bottom 3 maps) contribute more to their accessibilities.

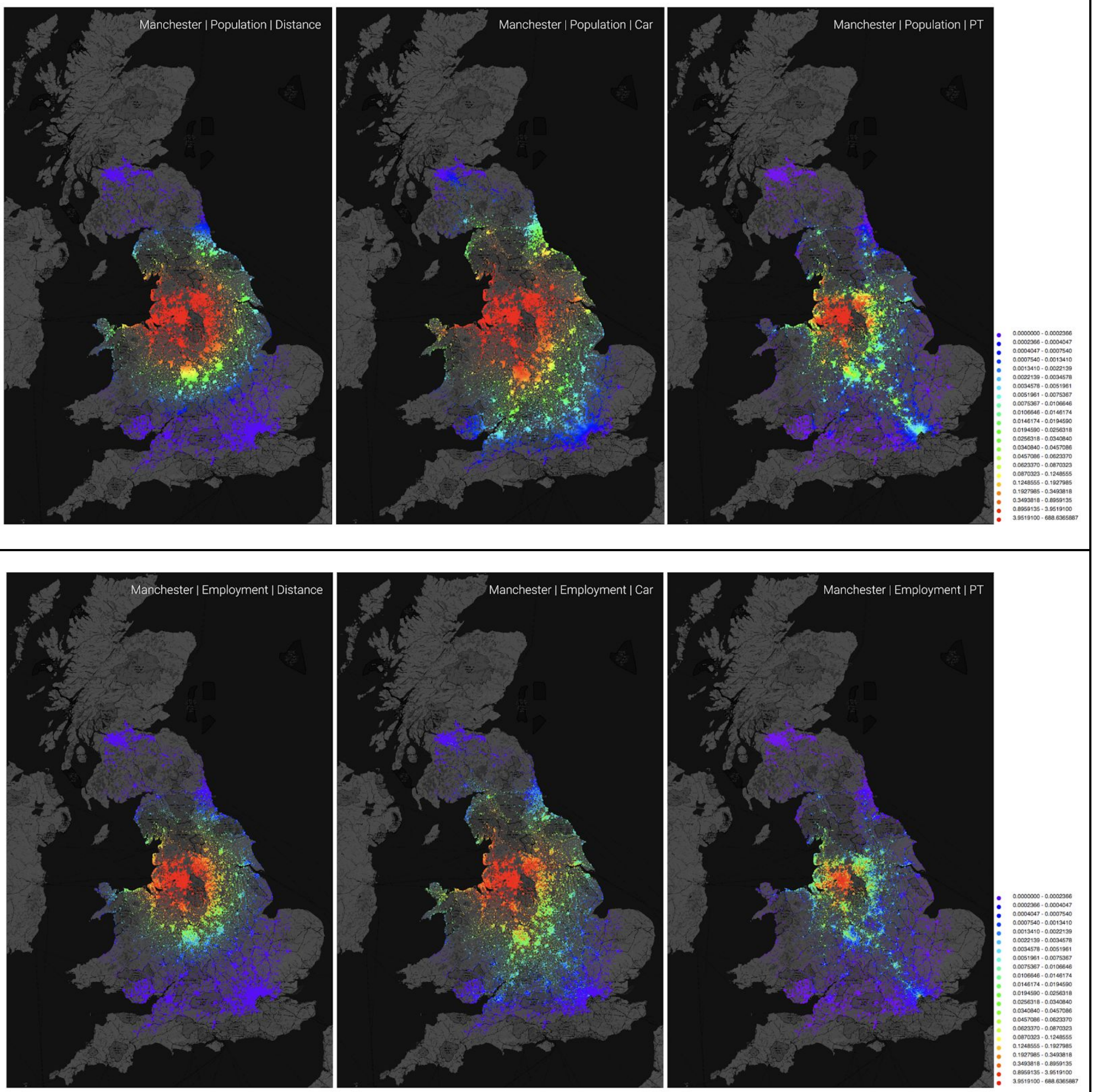
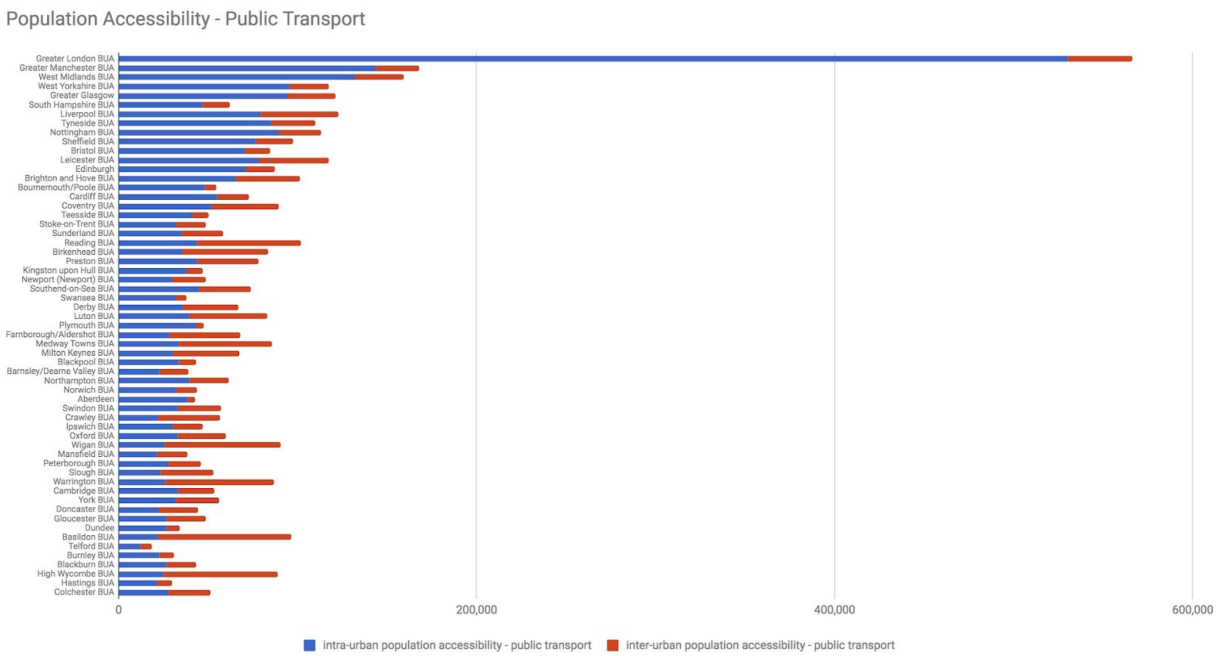


Figure 4. Population-base (top) and employment-based (bottom) accessibility contributions (2016) for the Manchester PUA (crow-fly, car, public transport)

Figure 4 shows the accessibility contribution of each demand location (population and employment -based demand) in the case of crow-fly distance based proximity (left side) and in the cases of car and public transport travel costs (centre and right). These can be compared to visualise the impact of the mode-specific transport infrastructure on accessibility. For example in the maps of figure 4 the impact of the direct express rail connection between London and Manchester translates into high PT-based accessibility contribution for Inner London demand locations despite the physical distance to Manchester.

3.3. Intra-urban and inter-urban accessibility

We aggregate the accessibility contributions of each OA to produce intra-urban and inter-urban accessibilities for each city. The following graphs (figures 5-6) show population and employment based intra-urban and inter-urban accessibilities for car and public transport for each PUA.



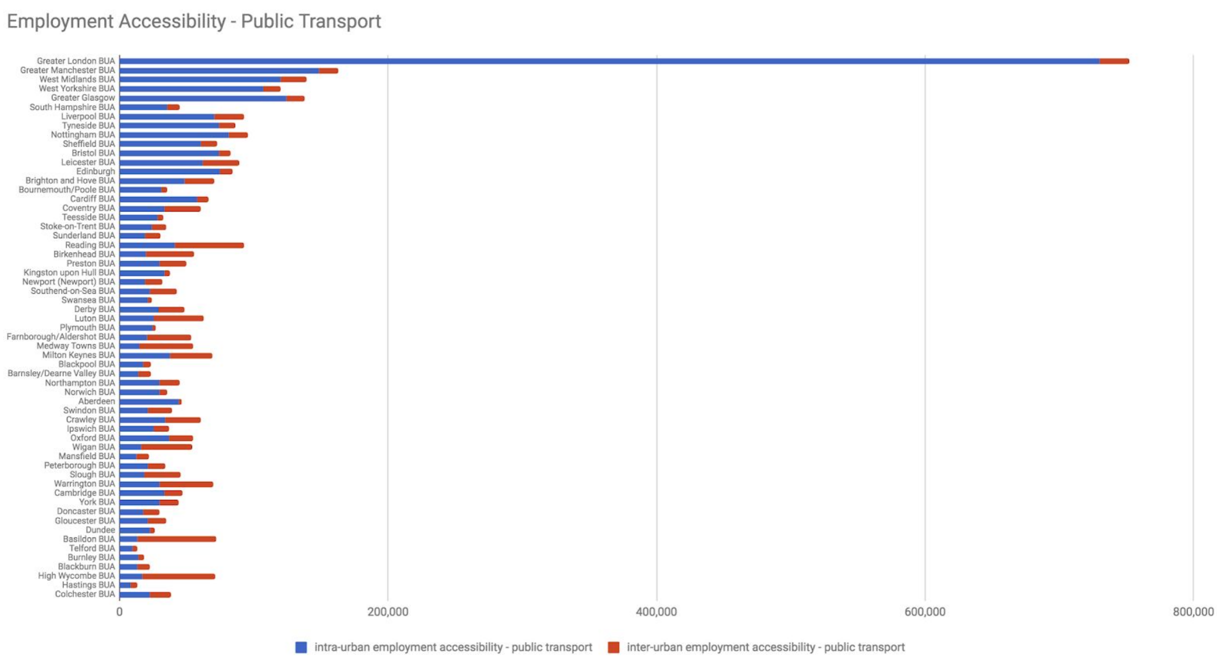


Figure 5. Population and employment public transport accessibilities for each of the PUAs (2016).

Figure 6. Population and employment car accessibilities for each of the PUAs (2016).

In figures 5 and 6 the length of each bar illustrates the total accessibility of the corresponding PUA's city centre. The blue segment represents the accessibility contribution of all demand locations inside the PUA (Output Areas inside the city boundaries as defined in appendix 1) and the red segment represents the accessibility contribution of all demand locations outside the boundaries of the city. The relative size of the two segments shows the balance of intra- and inter-urban accessibilities for each PUA; this represents how reliant a city is on demand from locations within and beyond its boundaries.

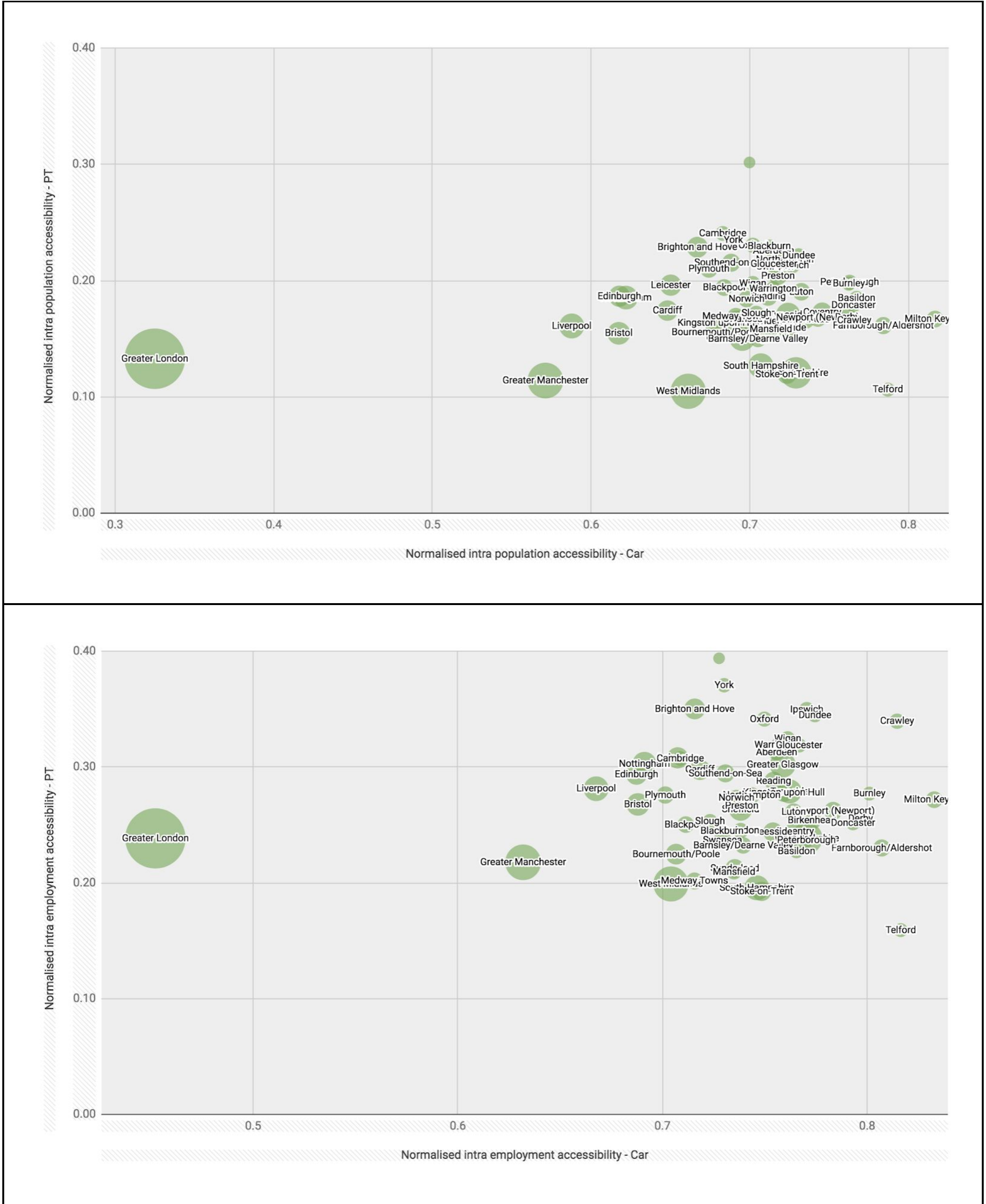


Figure 7. Car (x) versus Public Transport (y) normalised intra-urban accessibility (2016) for population-based (top) and employment-based (bottom) demand.

Once the car, public transport and crow-fly accessibilities of a city have been calculated, we can normalise car and public transport by crow-fly. The following graphs show, for each Primary Urban

Area (PUA), the ratios of "car to crow-fly" (x-axis) and "public transport to crow-fly" (y-axis) accessibilities for the intra-urban (green graphs), inter-urban (red graphs) and UK-wide (total - blue graphs) spatial levels. The size of each circle represents the population of the PUA. In each of the three figures, the top graph shows population based accessibilities (2016) and the bottom graph employment based accessibilities (2016).

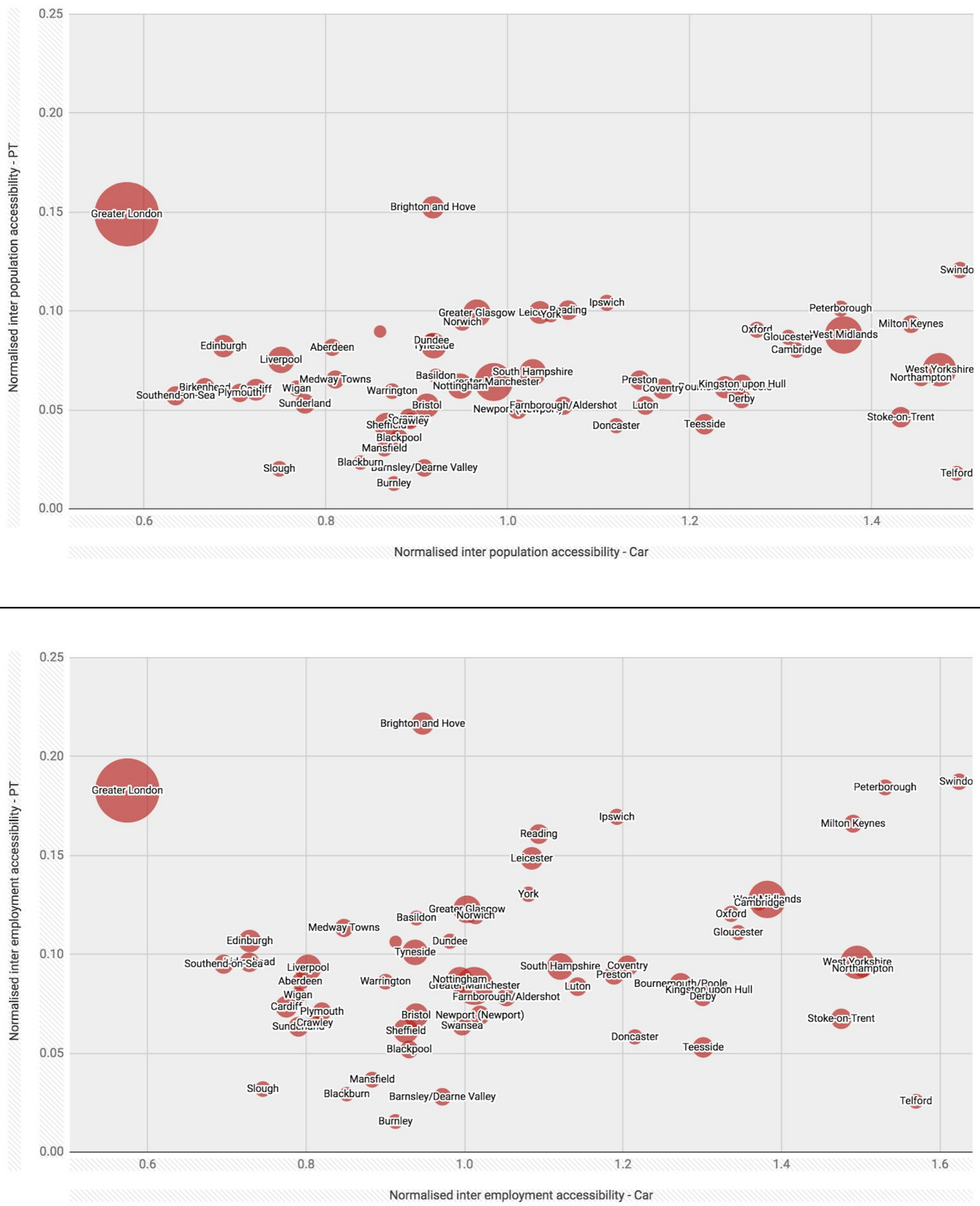
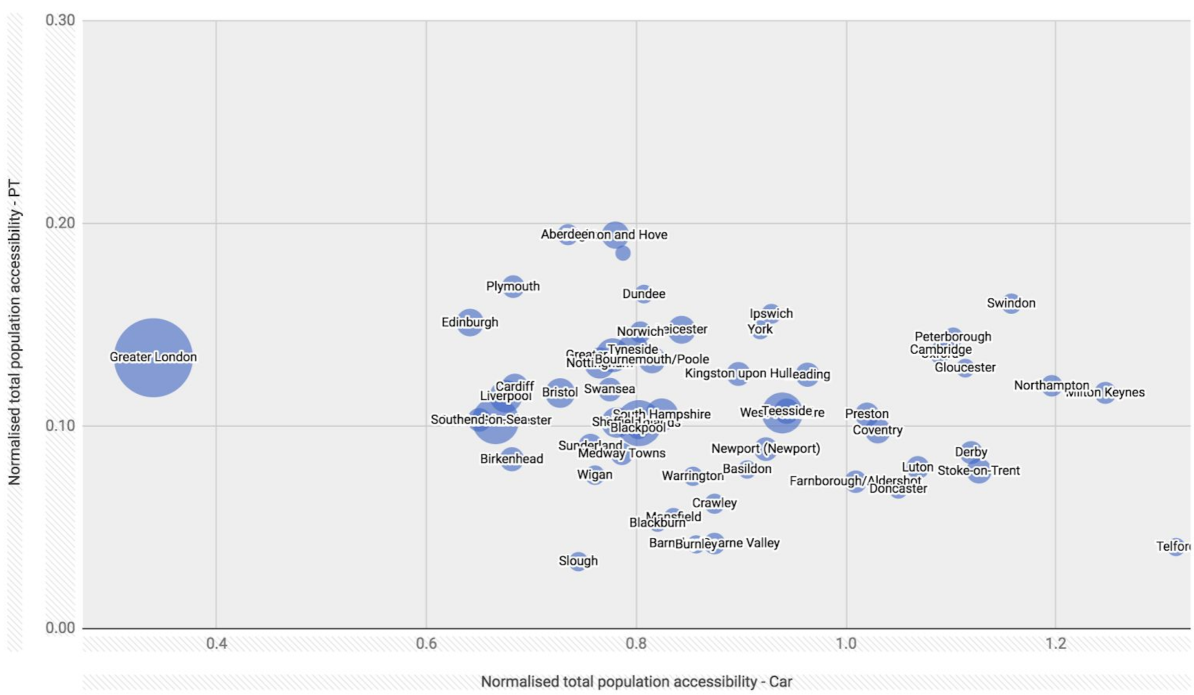


Figure 8. Car (x) versus Public Transport (y) normalised inter-urban accessibility (2016) for population-based (top) and employment-based (bottom) demand.



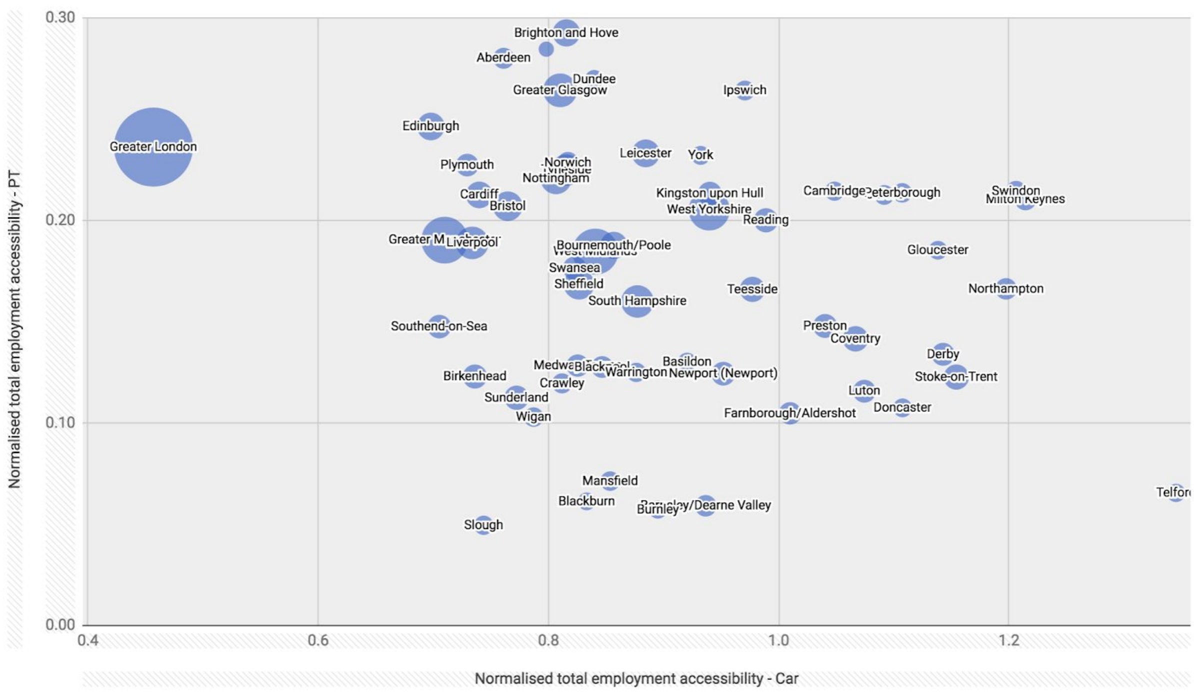


Figure 9. Car (x) versus Public Transport (y) normalised total accessibility (2016) for population-based (top) and employment-based (bottom) demand.

Intra-urban: London's car accessibility is particularly poor, while Birmingham (West Midlands) has very poor public transport accessibility.

Inter-urban: London's inter-urban public transport accessibility is particularly good, while Birmingham (West Midlands) and Leeds (West Yorkshire) have good inter-urban car accessibility.

3.4. Peak and Off-peak accessibility

Part of the analysis focuses on identifying road traffic congestion. We measure this by calculating the ratio of peak to off-peak accessibilities for each city. The following graphs show, for each Primary Urban Area (PUA), the ratios of peak to off-peak accessibility for the intra-urban (x-axis) and inter-urban (y-axis) spatial levels. The size of each circle represents the population of the PUA. The top graph shows population based accessibilities (2016) and the bottom graph employment based accessibilities (2016).

The new towns of Milton Keynes and Telford have good intra-urban peak accessibilities, while PUAs in the North East have good inter-urban peak accessibilities (compared to off-peak). London's intra-urban and inter-urban peak accessibilities are poor (compared to off-peak).

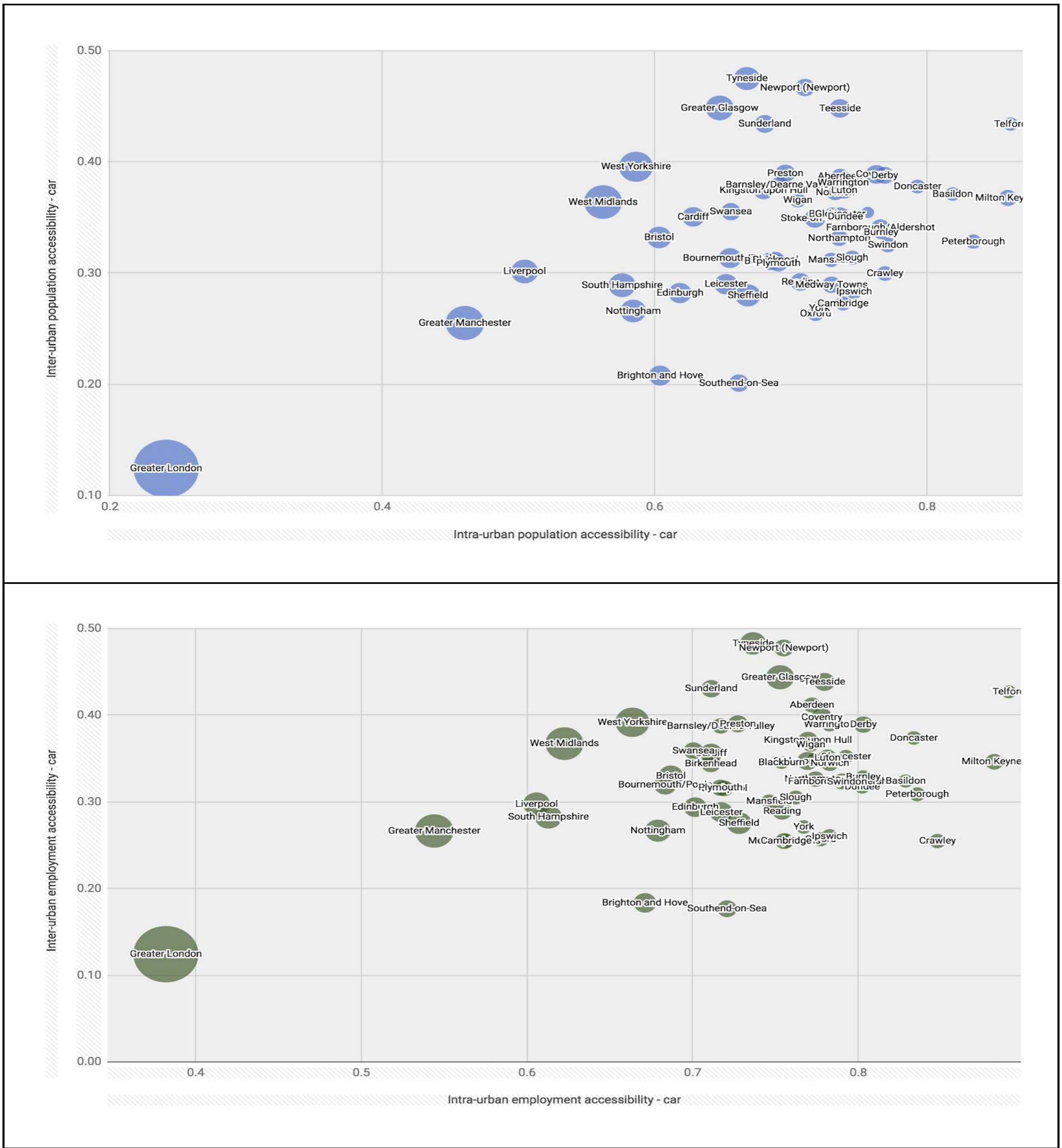


Fig 10. ***peak/off-peak*** **ratio for intra- and inter-urban accessibility (2016) | population (up), employment (down).**

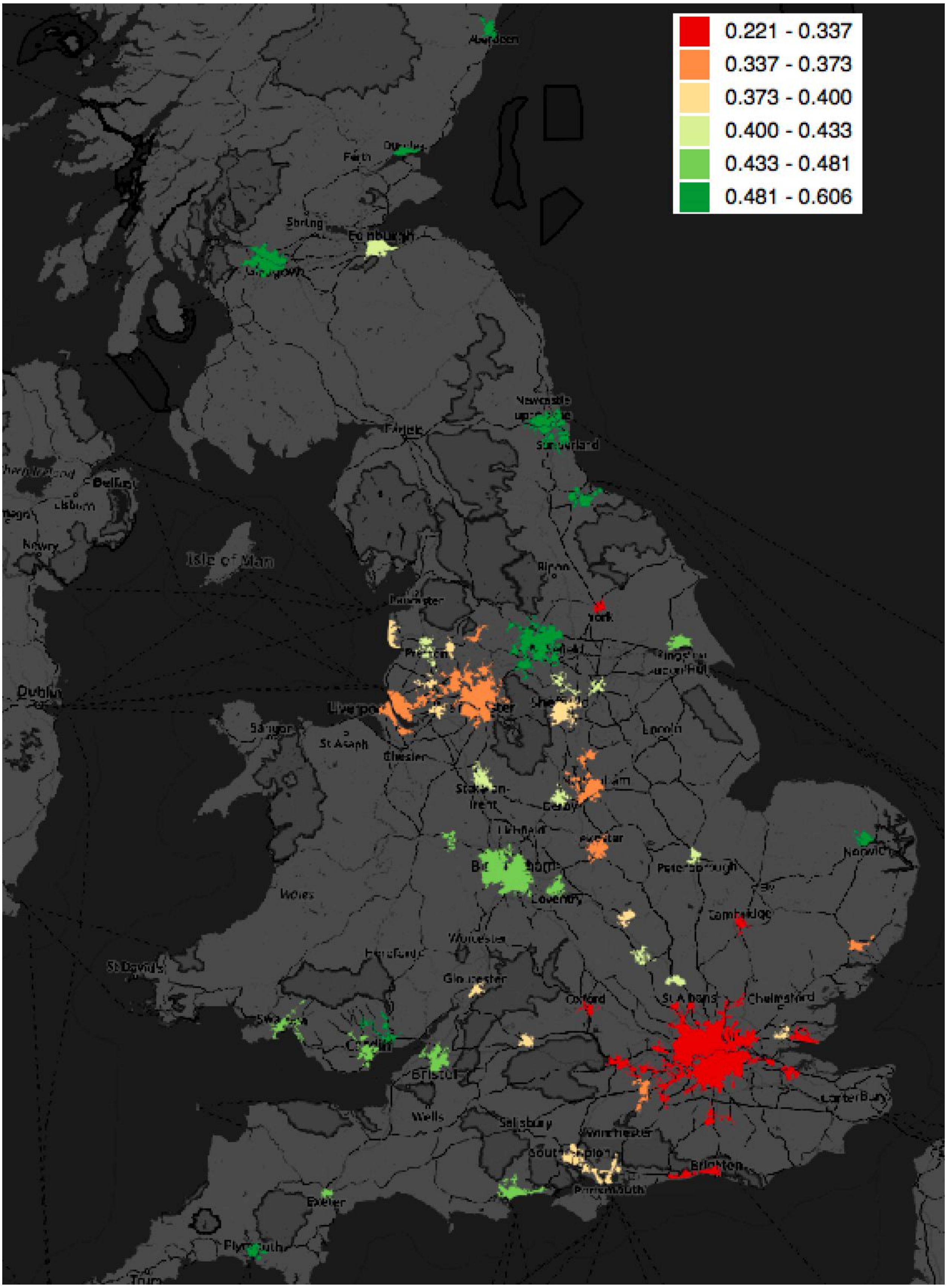


Figure 10.1. Map of ratio of peak-time versus free-flow total population-based accessibilities for each PUA.

3.5. Accessibility contribution by Primary Urban Area

By aggregating accessibility contribution at the level of Primary Urban Areas, we can discover strong and weak inter-urban connectivity and infrastructure relationships that highlight the performance of the transport network. For example in the matrix below, it is easy to identify the strong relative accessibility contribution of London to places such as Basildon, Crawley and Luton and Manchester's contribution to Blackburn, Blackpool and even Liverpool.

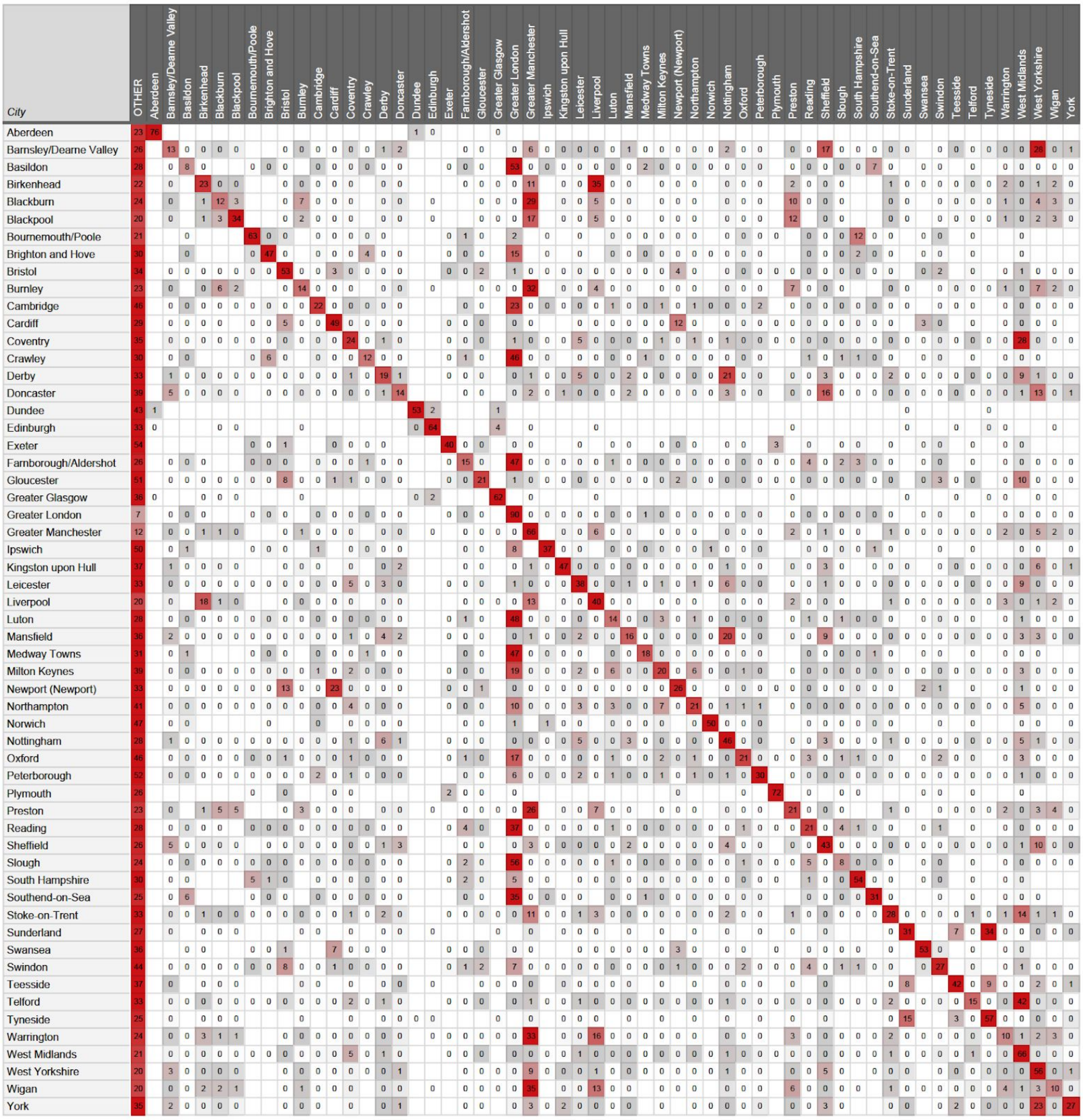


Figure 11. Contribution of Primary Urban Areas to the population accessibility of other Primary Urban Areas. Each cell states the percentile contribution of the column PUA to the accessibility score of the row PUA. The first column represents demand locations that are not within any PUA. White represents low, grey medium, pink high and red very high contribution.

Moreover, it is possible to identify relationships that are not as prominent as expected. The following graph shows the accessibility contribution of PUAs to Sheffield (top) and Sunderland (bottom) (left: car vs crow-fly, right: public transport vs crow-fly). Circles under the trend line represent PUAs that contribute less accessibility than expected based on their physical proximity and circles over the trend line represent PUAs that contribute more accessibility than expected based on their physical proximity. In the case of Sheffield, the car-based accessibility contribution from Manchester is affected by poor motorway connectivity between the two cities (large circle under the trend line at the top right side of the top left graph). In the case of Sunderland, the public transport-based accessibility contribution from Newcastle is affected by poor rail connectivity between the two cities (large circle under the trend line at the top right side of the bottom right graph).

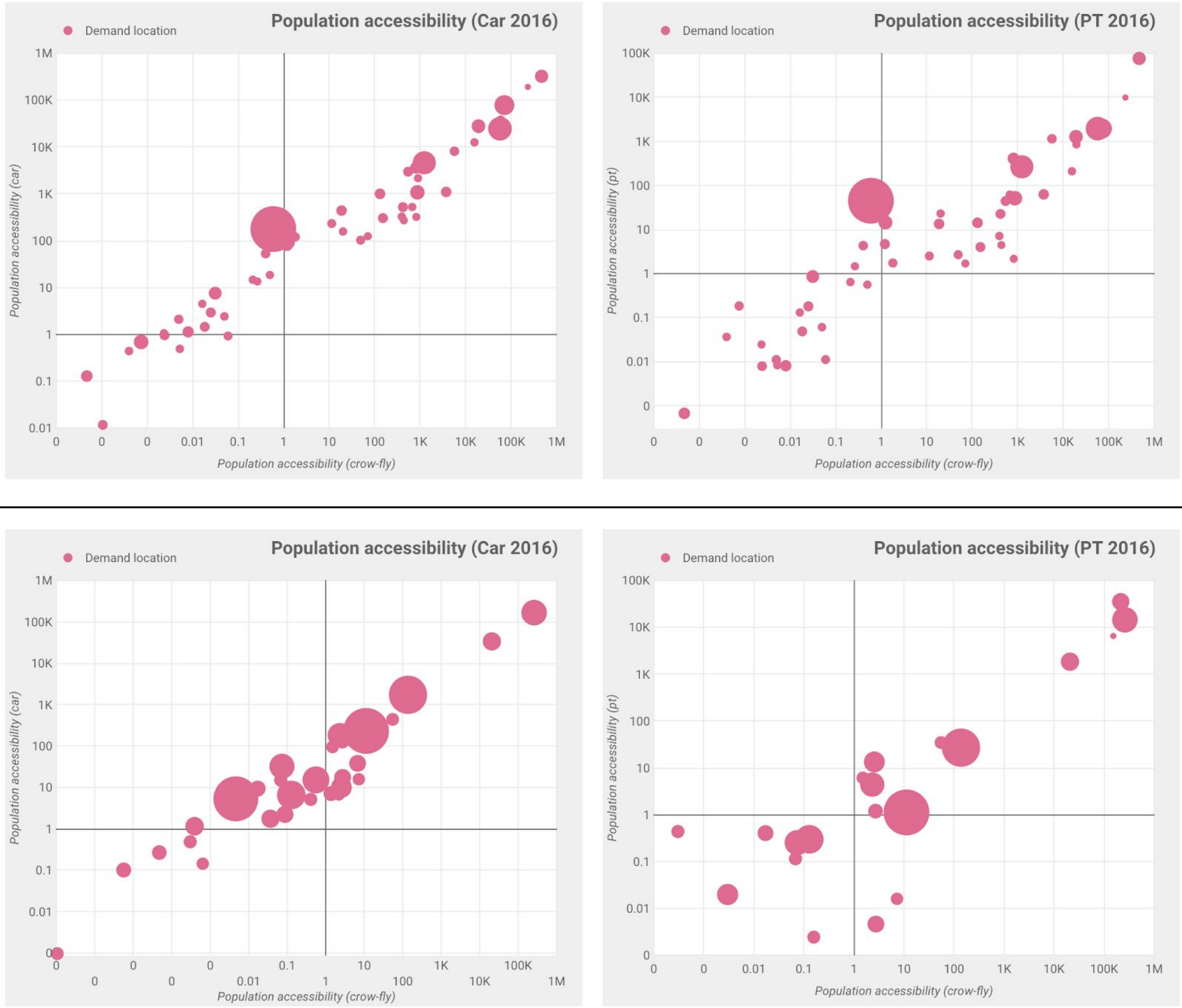


Figure 12. Contribution of each Primary Urban Area to the population accessibility of Sheffield (top) and Sunderland (bottom) | left: car vs crow-fly, right: public transport vs crow-fly.

3.6. Attractiveness

The attractiveness connectivity indicator provides a useful supplementary tool for estimating the ability of a city to contain its intra-urban demand and attract inter-urban demand from locations outside its boundaries. The following graphs show normalised population and employment based attractiveness (2016) for car (top) and public transport (bottom).

We normalise the inter-urban and intra-urban attractiveness scores by the PUA's population/employment size; therefore, values along the Y-axis represent the proportion of demand located inside the PUA that is attracted by it and the X-axis the amount of demand attracted from outside the PUA as a fraction of its size. For example, London contains the majority of its demand and, in the case of the public transport, attracts significantly more from outside.

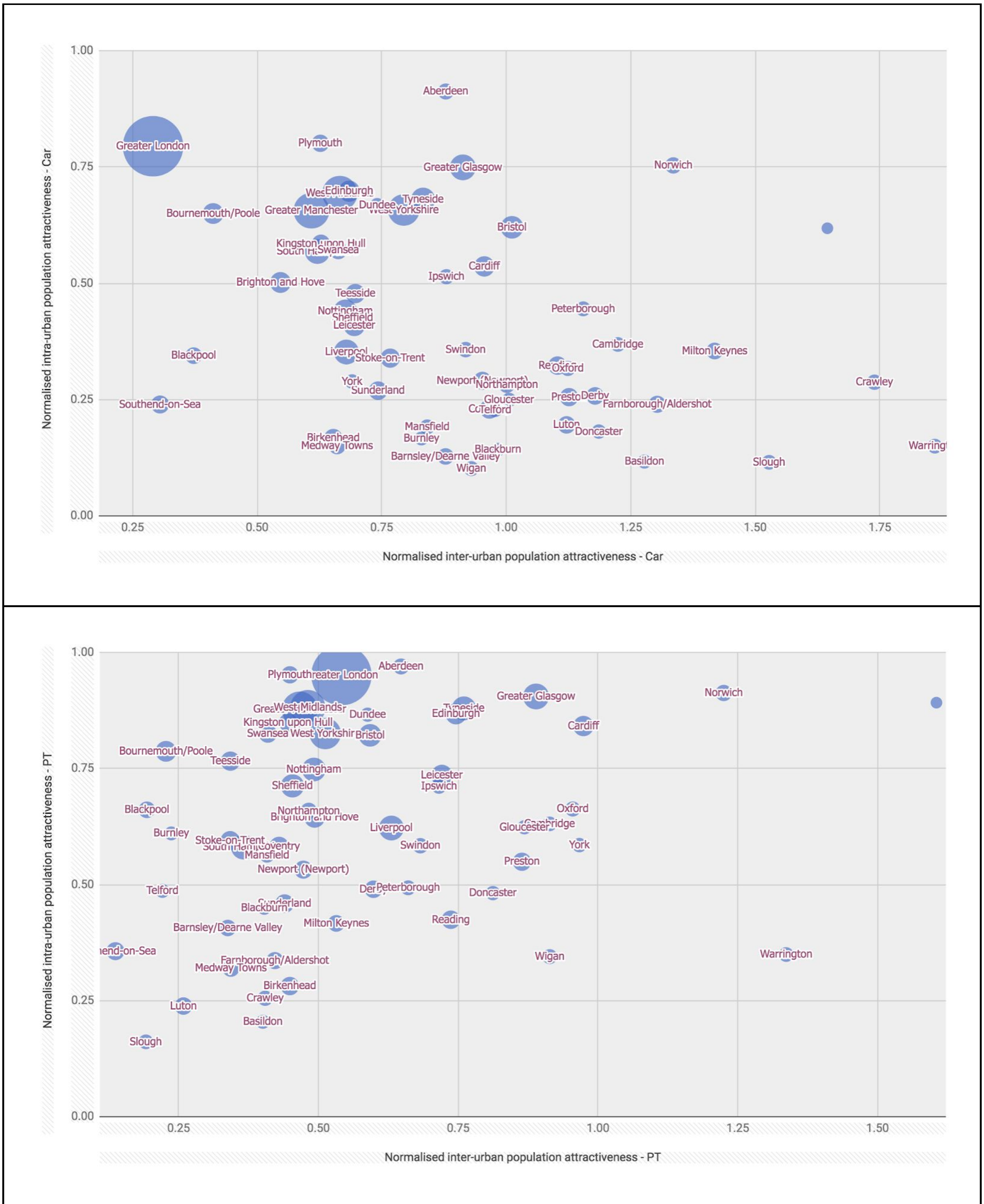


Figure 13. Population based attractiveness (2016) for car (top) and public transport (bottom). X-axis represents inter-urban attractiveness normalised by employment size of PUA and Y-axis represents intra-urban attractiveness normalised by employment size of PUA

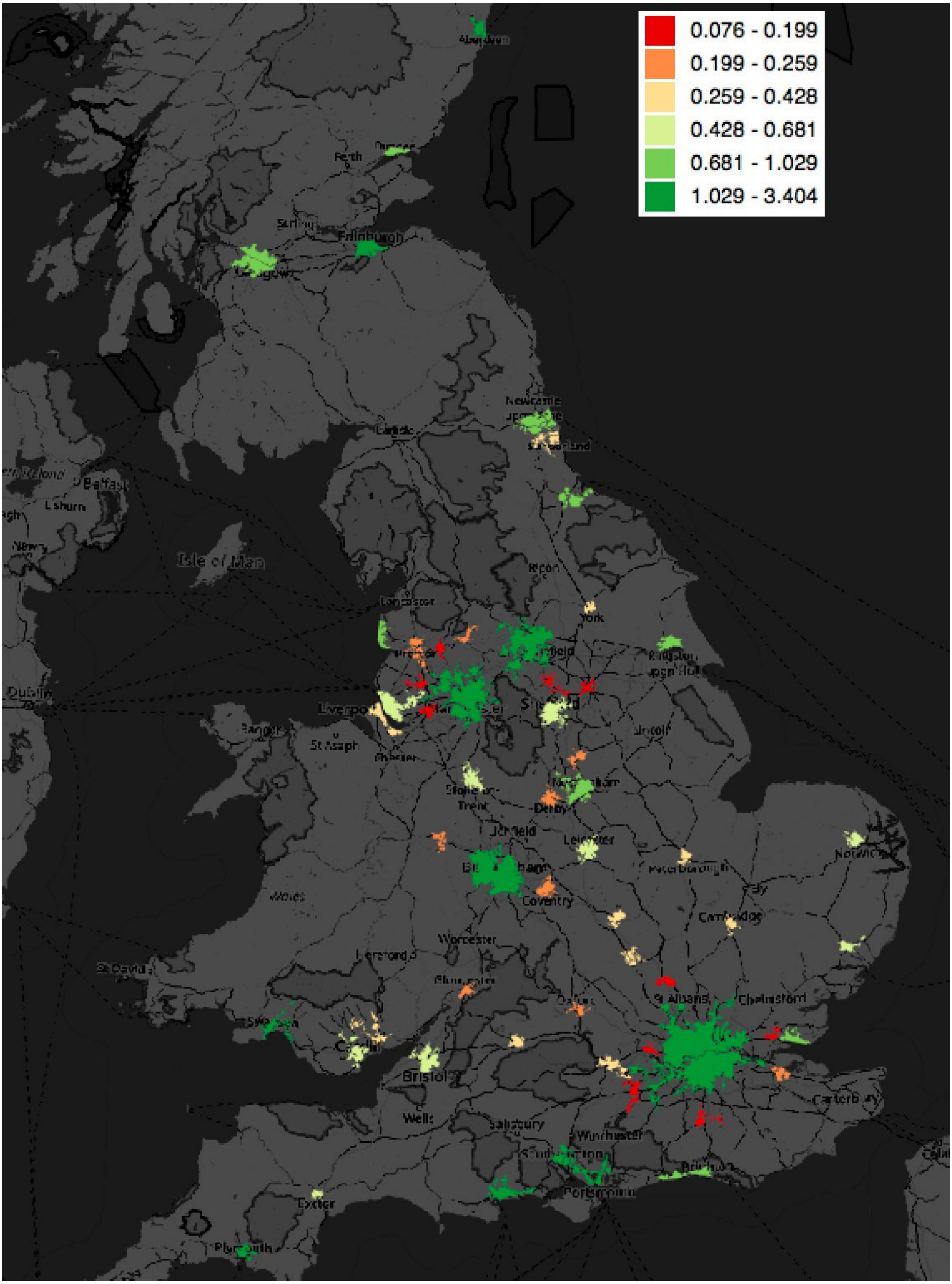


Figure 13.1. Map of ratio of intra- versus inter-urban total population-based multi-modal attractiveness for each PUA.

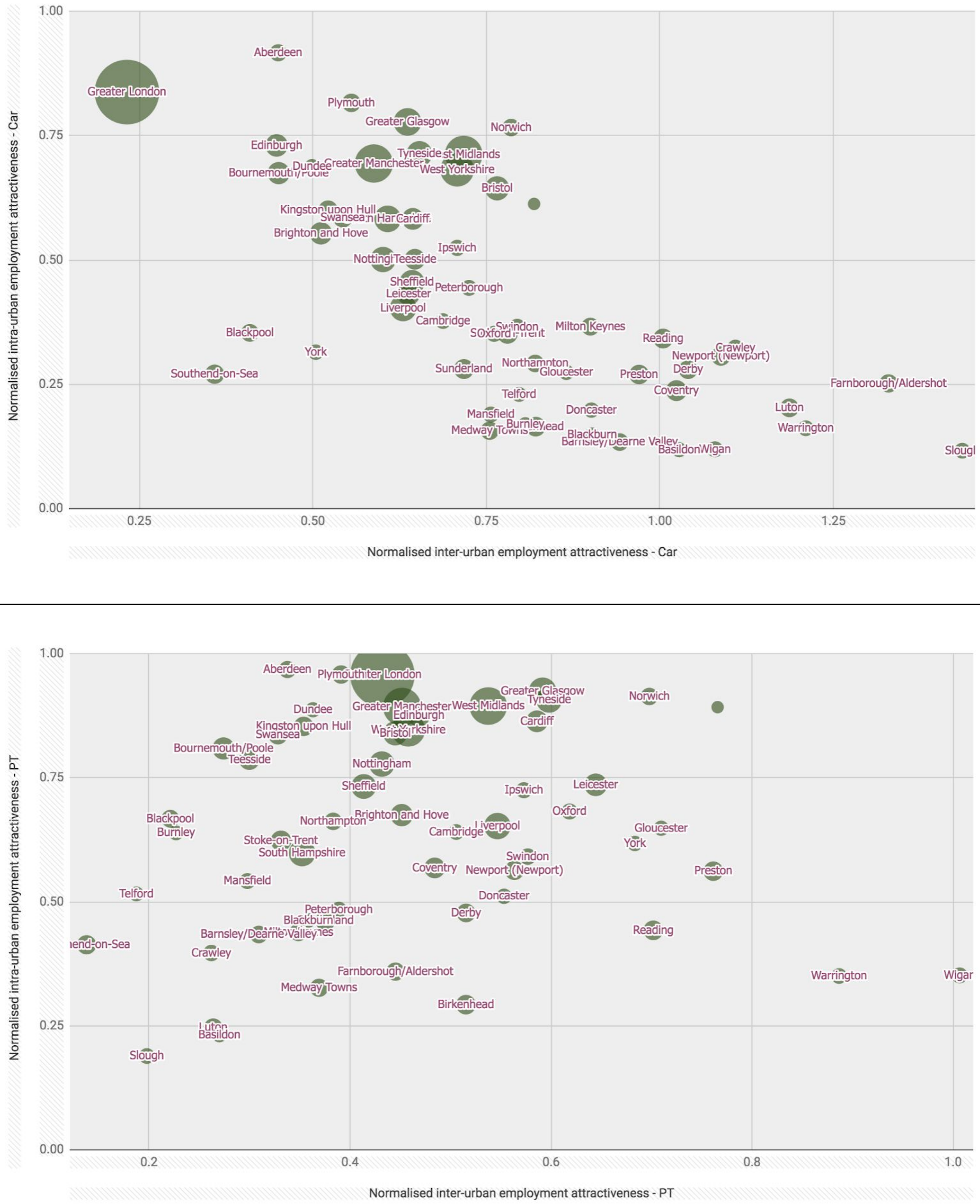


Figure 14. Employment based attractiveness (2016) for car (top) and public transport (bottom). X-axis represents inter-urban attractiveness normalised by employment size of PUA and Y-axis represents intra-urban attractiveness normalised by employment size of PUA

4. Conclusion

We have presented a methodology for developing transport performance indicators that indicate transport connectivity and have presented the results for the UK using this methodology. The outcome of the work will strengthen the Commission's ability to make objective and evidence-based policy recommendations on national priorities for transport investment.

To calculate travel times for each transport mode, we have utilised Prospective's multimodal transport network, which provides end-to-end (from location of demand to arrival to city centre) travel times both for free flow time and peak time travel speeds (for private transport) and takes into account walking and waiting time (based on service frequency) for public transport. The network combines (i) a detailed road network (contains every street segment and path in Great Britain), (ii) a full representation of the bus/coach/tram network (including every bus-stop, route and service in Great Britain), (iii) a full representation of the train/metro network (including every station and service in Great Britain), (iv) a full representation of the ferry network. These uni-modal networks are combined into a deeply integrated multimodal transport network through direct representation of all transit points (bus-stops, rail stations, ports, car parks etc.).Further details on Prospective's multimodal transport network can be found in Appendix A4.

From this underlying resource we have generated connectivity indicators that represent the effectiveness of a transport mode in facilitating access to demand from a city centre after the geographic proximity between settlements has been accounted for. In addition, by mapping the contribution any source of demand makes in the overall accessibility level of a city, we can highlight where physical infrastructure connectivity is stronger or weaker between specific pairs of settlements and reveal the performance of the transport network by each mode at a fine geographic scale. The combined metrics provide a framework for modelling the impact of market potential on increasing returns and geographic concentration and clarify the role of transport infrastructure in these relationships. In particular, highlighting how wages are associated with proximity to consumer markets and the importance of economies of scale in this process (for example, Hanson 2005).

We recommend further work to compare the accessibility and attractivity indicators for each BUA with recent estimates of income, workplace earnings and GVA compiled by the Centre for Cities for each Primary Urban Area (PUA) (lookup table between BUAs and PUAs in Appendix 5), thus exploring the extent to which income is related to accessibility. Such work would introduce an explicit link between scale economies and accessibility (Batty, 2013) relating the analysis to arguments about how accessibility can be related to levels of consumer demand (population).

Appendix 1: Defining built-up areas (BUA)

For England and Wales we use the Office for National Statistics 2011 Built-up Areas (Office for National Statistics 2013).

Technological advances since 2001, both in the underlying data and processing techniques, have meant that it has been possible to move away from the manual process used to identify the areas in the past to an automated method. This has enabled a more consistent, transparent and repeatable dataset to be produced. Ordnance Survey, the national mapping agency of Great Britain, were commissioned by a cross government working group (Office for National Statistics, Department for Communities and Local Government, Department for the Environment, Food and Rural Affairs, and Welsh Government) to create the digital boundaries for the 2011 built-up areas using an automated approach based on grid squares.

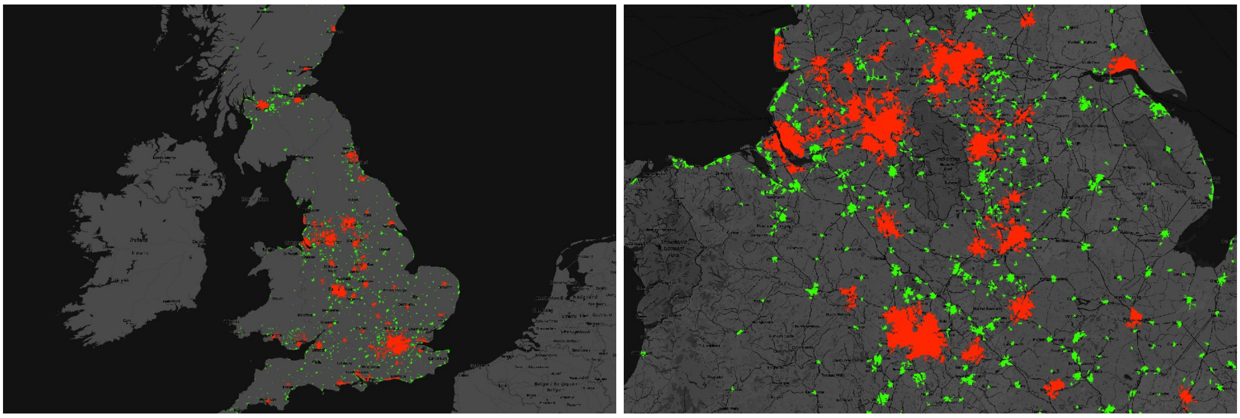


Figure 15. 1000 largest GB settlements (2011 population). Red colour: Primary Urban Areas (PUA) according to the Centre for Cities. Boundaries based on Office for National Statistics 2011 Built-up Areas and National Records of Scotland Settlements 2012.

Equivalently, for Scotland we use the National Records of Scotland Settlements (Urban Areas) in Scotland, published by Scottish Government Spatial Data Infrastructure in 2014. These are based on the mid-2012 small area population estimates published in December 2013 which were themselves based on results from the 2011 Census. The previous mid-2010 settlements and localities estimates were created using the mid-2010 small area population estimates which were based on population estimates rolled-forward from the 2001 Census (National Records of Scotland 2014).

Each of the 63 Primary Urban Areas, defined by the Centre for Cities, has been manually matched to a ONS/NRS Built-Up Area. The results of the matching process are presented in Appendix 5.

Appendix 2: Defining city centres

We define the city centre of each Built-Up Area (BUA) as a set of locations where commercial activity is exceptionally intense. In particular, for each BUA, we define as city centre, the set of 2011 Census Output Areas (OAs) which present the highest job density expressed as:

$$centrality\ score\ =\ workplace\ employment\ within\ 15\ minutes\ walk\ from\ the\ OA$$

For workplace employment in each 2011 Census OA, we use 2011 Census table WP101UKoa. Each OA is ranked according to its *centrality score* in relation to the rest of the OAs inside the same BUA.

The city centre is defined as the set of OAs with *centrality score* equal or higher than 99.8% of all OAs in the BUA (*city-centre OAs*). In almost all cases the set of city-centre OAs contains either a single OA, or a set of adjacent OAs. In the case of London, the set contains OAs in two distinct centres: West End and City of London.

A2.1. Calculating transport costs to multiple city-centre OAs

When a Built-Up Area (BUA) has more that one city-centre OAs, the transport cost between a location and the city centre of this BUA is defined as the mean travel cost between this location and the city-centre OAs of the BUA.

A2.2. Estimating the size of a city centre

To calculate the attractiveness of the city centre of a BUA (for the attractiveness metric) we must estimate the size of the city centre.

For the intra-city set of indicators, the size of the city centre for either 2011 or 2016 is calculated as the total workplace employment for this year that is both:

1. Within 15 minutes walk from any of the BUA’s city-centre OAs.
2. Within the boundaries of the specific BUA.

For the inter-city and international set of indicators, the size of the city centre for either 2011 or 2016 is calculated as the total workplace employment for this year that is within the boundaries of the specific BUA; i.e. the total workplace employment of the specific BUA.

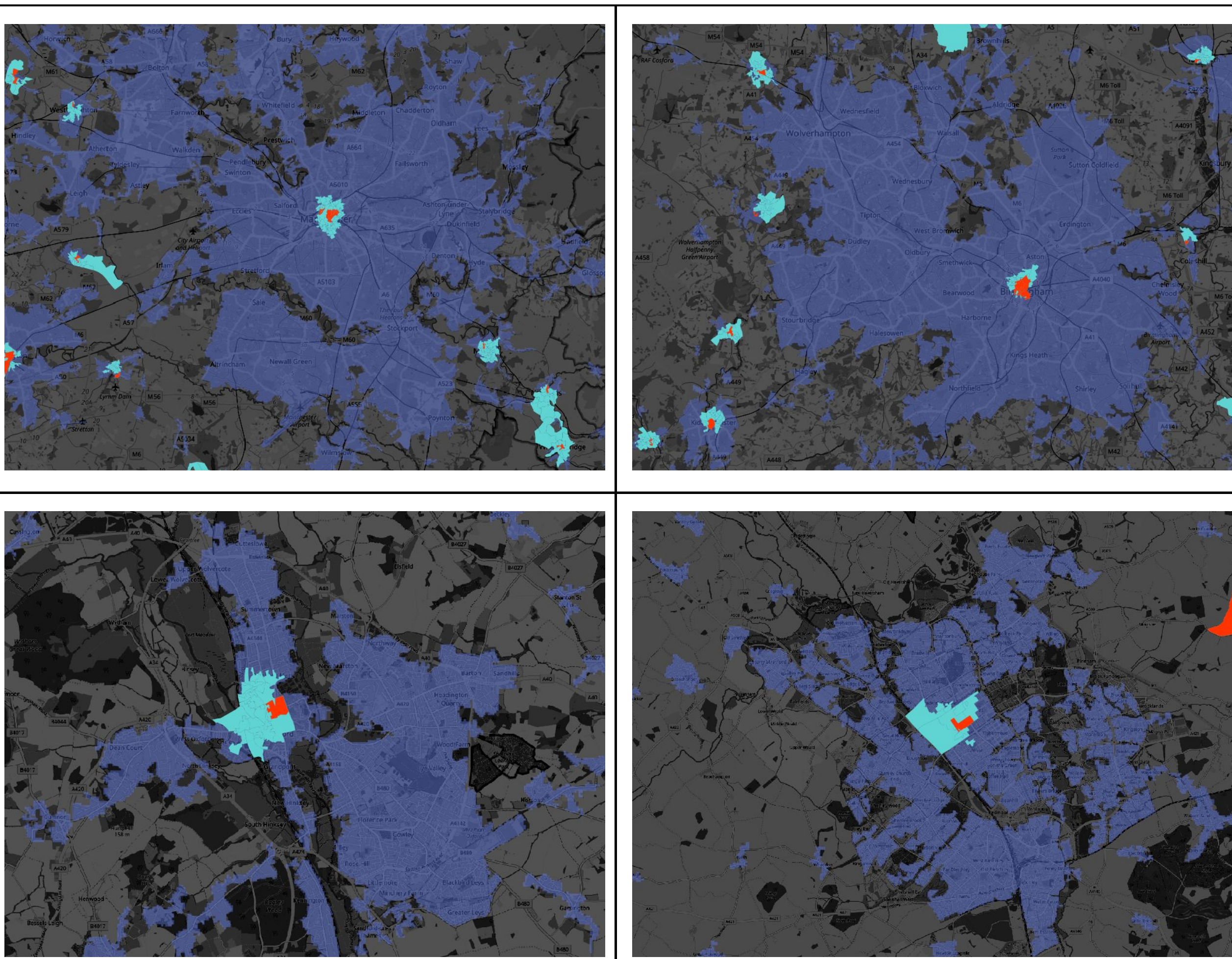


Figure 16. City centre size. All employment within 15 mins from city centre OAs by public transport | Red polygons: city centre, Cyan polygons: city centre reach, Blue polygons: city boundaries | Top left: Manchester, top right: Birmingham, bottom left: Oxford, bottom right: Milton Keynes

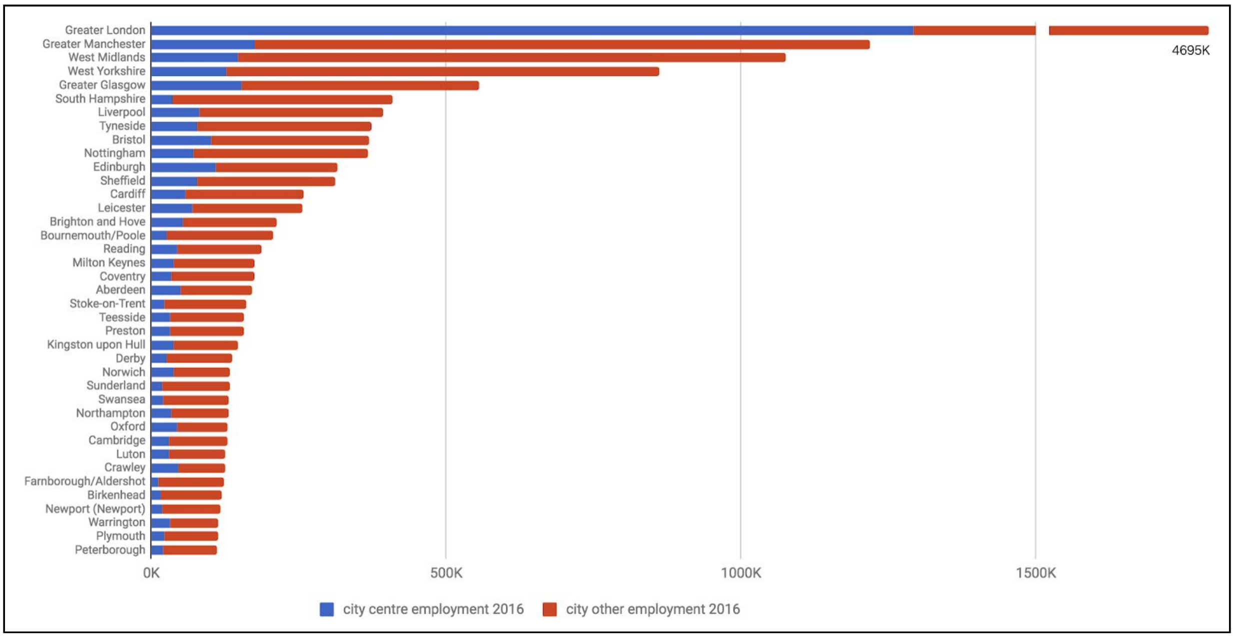


Figure 17. Comparing workplace employment within city centres (blue) and the rest of the built-up area (red).

Appendix 3: Estimating demand

This appendix describes the methods and data that will be used to estimate intermediate (based on workplace employment) and final (based on resident population) demand across Great Britain.

A3.1. Estimating residential population

For 2011 resident population we use 2011 England & Wales (ONS) and Scotland (NRS) Census data on population by age (Census table: KS101UKoa) at the Census 2011 Output Area (OA11) level.

To estimate the current resident population we use the latest releases (mid-2016) of the Lower Super Output Area Mid-Year Population Estimates (ONS) for England and Wales and of the Small Area Population Estimates (NRS) for Scotland, both of which provide population estimates by age at the LSOA level. We use the 2011 resident population Census table (KS101UKoa) to distribute the 2016 resident population estimates from the LSOA to the OA level.

A3.2. Estimating workplace population

For 2011 workplace employment, we use 2011 England & Wales (ONS) and Scotland (NRS) Census data on workplace employment (Census table: WP101UKoa) at the Census 2011 Output Area (OA11) level.

To estimate the current workplace employment we use the Business Register and Employment Survey which provides job estimates by industry at the LSOA level. We use the 2011 workplace employment Census table (WP101UKoa) to distribute the 2016 workplace employment estimates from the LSOA to the OA level.

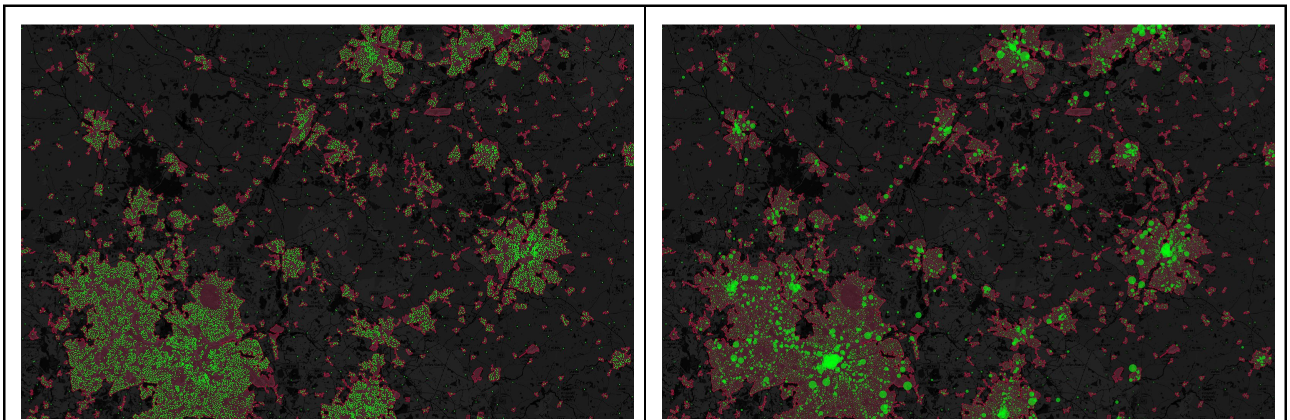


Figure 18. Left: 2011 Census Output Area (OA11) population-weighted centroids inside settlements used to define settlement city centres. Right: Workplace employment demand visualised using variable circle sizes for each OA11 centroid.

Appendix 4: The multimodal transport network

A4.1. Structure

Prospective's multimodal transport network combines (i) a detailed road network (contains every street segment and path in Great Britain), (ii) a full representation of the bus/coach/tram network (including every bus-stop, route and service in Great Britain), (iii) a full representation of the train/metro network (including every station and service in Great Britain), (iv) a full representation of the ferry network.

These uni-modal networks are combined into a deeply integrated multimodal transport network through direct representation of all transit points (bus-stops, rail stations, ports, car parks etc.).

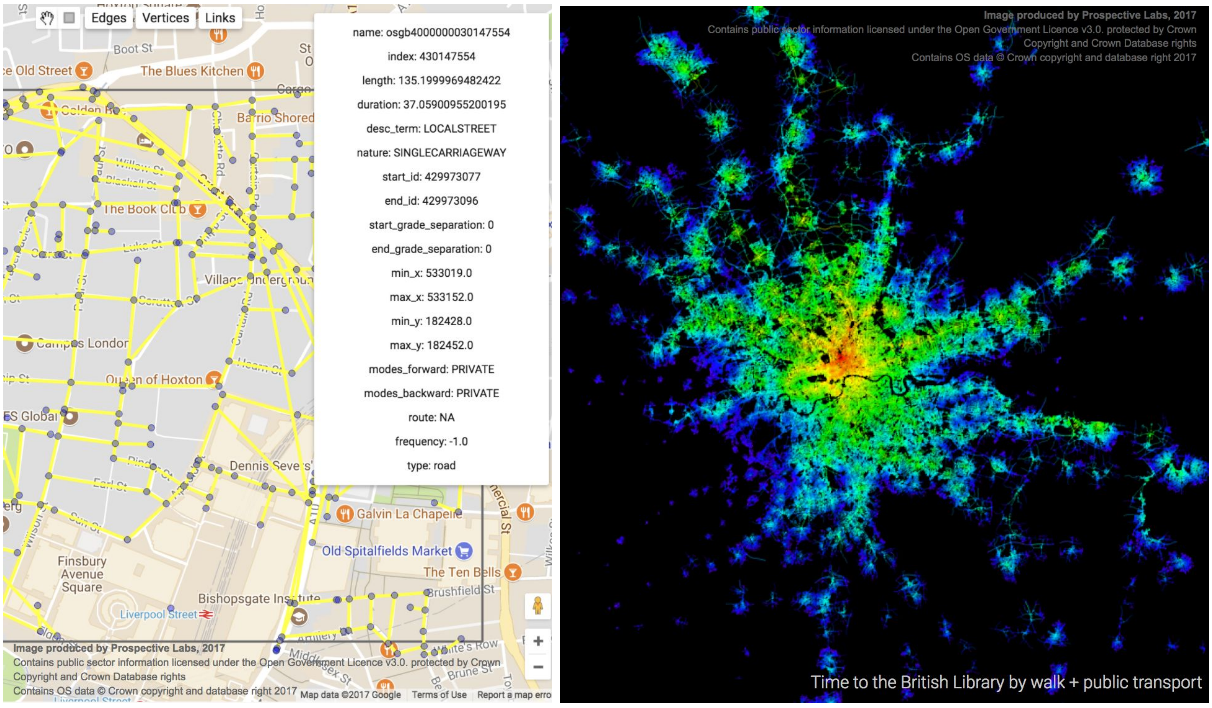


Figure 19. Prospective's multimodal transport network: A spatio-temporal granular representation of all the entities which make up a multimodal transport infrastructure

A4.2. Modelling capabilities

The deeply integrated multimodal network allows the development of complex cross-modal trip scenarios; e.g. model the routing behaviour of passengers using multiple (private and/or public) transport modes to reach their destinations and test the impact of their combined decisions. The versatility of this approach allows users to ask diverse what-if transport infrastructure questions, such as what is the impact of (i) a new bike-sharing rack on cycling volumes, (ii) a new bus lane on bus ridership, or (iii) road tolls on private car traffic.

A4.3. Data

The UK multimodal network is based on data from the following sources: Ordnance Survey (road network, routing information and urban paths - updated every 6 weeks), Travelline (bus, coach, tram, and light rail timetable data - updated weekly), The Rail Delivery Group (rail timetable data - updated weekly).

Appendix 5: Centre for Cities lookup table

Table includes all ONS built-up areas with 2016 population over 100,000.

Built-Up Area code	Built-Up Area (BUA) name	Population 2016	Employment 2016	Population 2011	Employment 2011	Centre for Cities Primary Urban Area (PUA) name(s)
E34004707	Greater London BUA	10,461,570	5,986,919	9,765,061	5,222,399	London
E34005054	Greater Manchester BUA	2,640,505	1,217,957	2,541,936	1,163,783	Manchester
E34005001	West Midlands BUA	2,529,634	1,076,073	2,436,159	1,039,158	Birmingham
E34004684	West Yorkshire BUA	1,828,658	861,944	1,766,208	852,298	Leeds, Bradford, Huddersfield, Wakefield
S20000732	Greater Glasgow	1,001,582	555,615	966,155	508,232	Glasgow
E34004977	South Hampshire BUA	889,901	408,234	849,580	400,882	Portsmouth, Southampton
E34004801	Liverpool BUA	884,460	393,694	862,937	384,041	Liverpool
E34004998	Tyneside BUA	790,294	372,746	771,453	368,975	Newcastle
E34004946	Nottingham BUA	759,189	367,483	727,467	331,305	Nottingham
E34004969	Sheffield BUA	707,167	312,351	682,234	316,863	Sheffield
E34004965	Bristol BUA	651,684	369,729	613,699	337,780	Bristol
E34004647	Leicester BUA	530,095	255,953	506,379	238,449	Leicester
S20000682	Edinburgh	512,492	316,439	482,523	290,009	Edinburgh
E34004748	Brighton and Hove BUA	495,954	213,175	473,661	214,872	Brighton, Worthing
E34005031	Bournemouth/Poole BUA	486,119	207,034	464,131	202,408	Bournemouth
W37000384	Cardiff BUA	462,410	259,036	445,503	246,384	Cardiff
E34004855	Coventry BUA	392,983	173,915	356,164	163,110	Coventry
E34004802	Teesside BUA	381,763	156,789	375,770	164,286	Middlesbrough
E34004612	Stoke-on-Trent BUA	378,744	160,242	371,295	161,005	Stoke
E34004630	Sunderland BUA	337,516	133,030	334,498	141,852	Sunderland
E34004640	Reading BUA	329,081	185,996	315,746	160,440	Reading
E34004654	Birkenhead BUA	326,796	119,422	324,889	123,321	Birkenhead
E34005039	Preston BUA	318,467	156,152	309,877	155,961	Preston
E34004839	Kingston upon Hull BUA	316,824	147,865	313,319	148,313	Hull
W37000385	Newport (Newport) BUA	310,495	117,626	305,517	121,156	Newport
E34005046	Southend-on-Sea BUA	304,144	102,588	294,764	109,807	Southend
W37000427	Swansea BUA	303,762	131,487	297,713	132,586	Swansea
E34004638	Derby BUA	278,428	136,847	270,080	128,988	Derby
E34004983	Luton BUA	275,289	125,090	257,706	111,717	Luton

E34005012	Plymouth BUA	267,349	112,527	259,560	123,258	Plymouth
E34004885	Farnborough/Aldershot BUA	257,769	124,088	251,497	117,055	Aldershot
E34005040	Medway Towns BUA	255,822	90,006	243,196	91,735	Chatham
E34005056	Milton Keynes BUA	241,780	174,354	227,967	134,818	Milton Keynes
E34004900	Blackpool BUA	238,109	94,170	238,458	98,929	Blackpool
E34004869	Barnsley/Dearne Valley BUA	231,343	90,121	221,051	89,246	Barnsley
E34004611	Northampton BUA	228,087	130,825	214,571	118,202	Northampton
E34004893	Norwich BUA	224,013	134,056	211,797	124,617	Norwich
S20000504	Aberdeen	213,795	171,558	207,496	153,630	Aberdeen
E34004828	Swindon BUA	191,995	103,489	184,322	95,514	Swindon
E34004880	Crawley BUA	187,735	124,886	178,609	110,748	Crawley
E34004730	Ipswich BUA	181,817	90,223	178,835	88,969	Ipswich
E34004572	Oxford BUA	181,068	129,293	170,611	106,286	Oxford
E34004959	Wigan BUA	176,430	64,995	173,135	70,001	Wigan
E34004765	Mansfield BUA	175,626	79,774	169,455	78,934	Mansfield
E34004715	Peterborough BUA	175,621	111,400	162,614	93,765	Peterborough
E34004940	Slough BUA	170,345	92,738	162,679	82,613	Slough
E34004251	Warrington BUA	170,199	113,824	164,549	97,250	Warrington
E34004798	Cambridge BUA	168,064	128,373	157,529	115,714	Cambridge
E34005036	York BUA	162,861	91,516	153,411	88,015	York
E34004696	Doncaster BUA	160,664	84,762	157,545	84,263	Doncaster
E34004693	Gloucester BUA	158,346	82,193	148,640	80,702	Gloucester
S20000665	Dundee	158,249	79,493	156,943	79,773	Dundee
E34004645	Basildon BUA	152,760	74,775	144,269	71,761	Basildon
E34004622	Telford BUA	151,469	75,266	145,876	72,779	Telford
E34004743	Burnley BUA	150,543	64,293	148,780	64,334	Burnley
E34004557	Blackburn BUA	145,459	66,104	145,989	63,067	Blackburn
E34004704	High Wycombe BUA	136,908	67,614	131,899	61,472	-
E34004625	Hastings BUA	136,140	43,929	132,840	50,798	-
E34005048	Colchester BUA	133,278	65,946	121,488	64,757	-
E34004917	Grimsby BUA	132,435	54,326	133,002	57,359	-
E34004846	Thanet BUA	131,338	38,473	125,062	42,425	-
E34004858	Exeter BUA	128,288	93,291	116,883	82,776	Exeter
E34004970	Burton upon Trent BUA	127,543	50,283	121,252	52,647	-

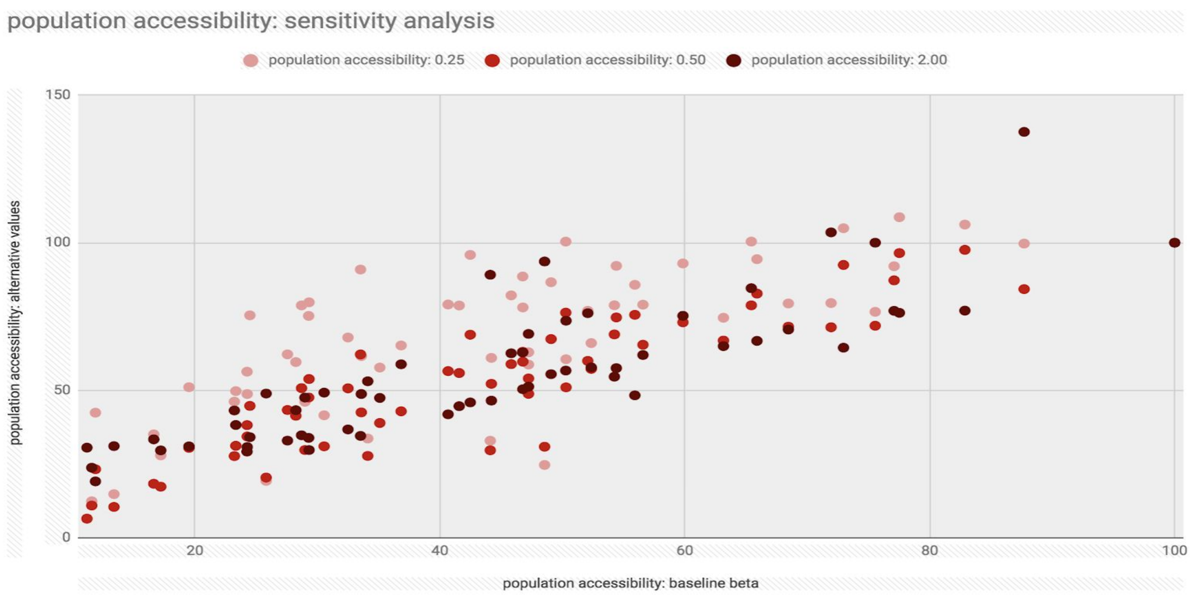
S20000864	Motherwell and Bellshill	124,911	51,750	123,380	56,891	-
E34004905	Accrington/Rossendale BUA	123,754	39,545	122,085	43,243	-
E34004862	Eastbourne BUA	122,623	43,173	117,580	47,824	-
E34005030	Lincoln BUA	120,615	68,673	114,601	68,450	-
E34004813	Paignton/Torquay BUA	117,695	43,652	114,879	46,452	-
E34003710	Cheltenham BUA	117,619	68,111	115,797	63,681	-
E34004924	Chelmsford BUA	116,073	65,004	111,187	61,767	-
E34004399	Maidstone BUA	115,886	56,242	107,226	56,559	-
E34005009	Basingstoke BUA	113,190	61,768	106,789	62,877	-
E34004985	Chesterfield BUA	112,892	50,403	112,257	53,026	-
E34004993	Bedford BUA	112,884	59,284	106,645	56,275	-
E34004941	Worcester BUA	104,846	54,199	101,165	53,721	-
S20000693	Falkirk	102,516	49,548	99,253	45,349	-
E34004686	Lancaster/Morecambe BUA	102,119	40,248	96,842	40,951	-

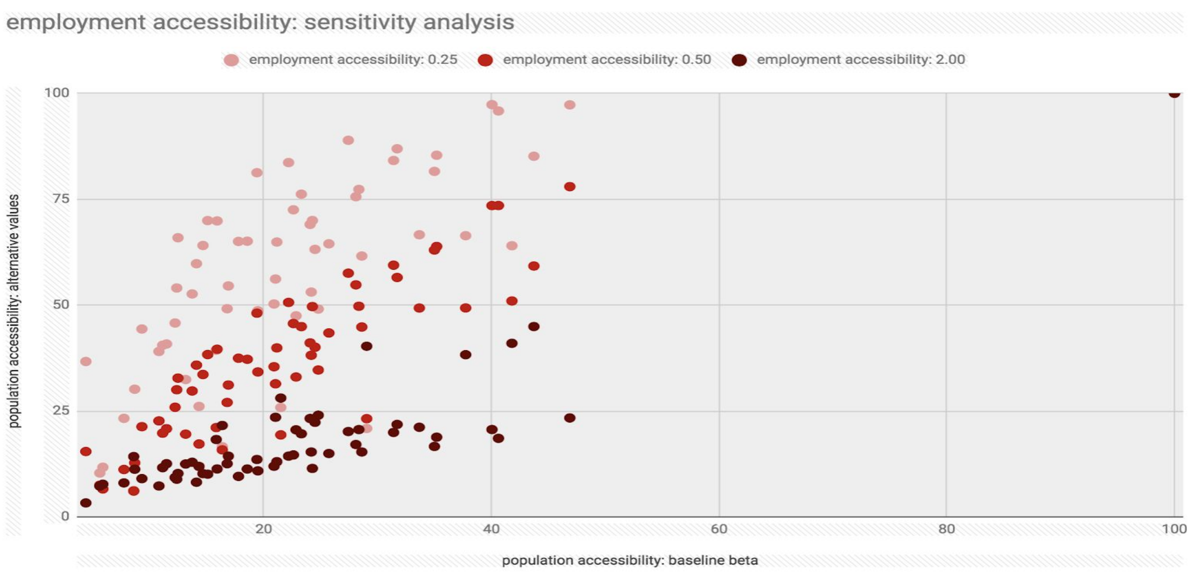
Appendix 6: Impact of distance (sensitivity analysis)

A6.1. Values

β_p represents that impact of distance/travel time on the attractiveness of city centre i to consumers in j. In first instance, the value of β_p is set so that the weighted average journey travel time across all transport modes and city centre i / destination j combinations is equal to the average journey travel time in Great Britain (across all trip purposes).

For the crow-fly accessibility calculations, β_p is set to represent equivalent average journey travel time under speed equal to 50 km/hr.





Population & employment accessibility scores (2016) for the Primary Urban Areas under different β_p values.

A6.2. Sensitivity

In order to determine how sensitive the results of the analysis are in relation to assumptions about the impact of distance (values for β_p) we have calculated the 2016 population and employment accessibility scores for all Primary Urban Areas (PUA) for different values of β_p: 0.25, 0.50 and 2.00 times the original value (in order to cover a wide range of values).

In order to compare the relative impact of the β_p on the selected connectivity indicators (2016 population and employment accessibilities) we index the results by dividing them with the respective score for London (beta_accessibility_PUA / beta_accessibility_London).

The results show that despite significant variation in the indexed score for different β_p values, the rank of each PUA remains relatively stable; i.e. a Primary Urban Area with relatively low accessibility score (compared to other PUAs) for one β_p value is likely to have relatively low accessibility scores for other β_p values.

References

Batty, M. (2013) A Theory of City Size, Science, 340-1418-1419.

Centre for Cities (2016) Cities Outlook 2016

Hansen, W.G. (1959) How Accessibility Shapes Land Use, Journal of the American Institute of Planners, 25, No. 2, 73-76.

Hanson, G.H. (2005). Market Potential, Increasing Returns and Geographic Concentration. Journal of International Economics, 67(1), 1-24.

Harris, C.D. (1954) The Market as a Factor in the Localization of Industry in the U.S., Annals of the Association of American Geographers, 44, no. 4, 315-348.

Krugman, P. (1992) Geography and Trade, The MIT Press, Cambridge MA.

McFadden, D. (1974) The Measurement of Urban Travel Demand, Journal of Public Economics, 3, 303-328

National Infrastructure Commission (2017) Economic growth and demand for infrastructure services

National Records of Scotland (2014) Background Information - Settlements and Localities

Office for National Statistics (2013) 2011 Built-up Areas - Methodology and Guidance (2013 v1)

Office for National Statistics (2017) United Kingdom Annual Accounts - The Blue Book

Stewart, J.Q. (1941) An Inverse Distance Variation for Certain Social Influences, Science, 93, 2404, 89-90.

Warntz, W.W. (1959) Toward a Geography of Price: A Study in Geo-econometrics, University of Pennsylvania Press, Philadelphia PA.