prospective

Transport Connectivity

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Table of Contents

Table of Contents 2

Executive Summary 5

1. Introduction 7

2. Methodology 8
- 2.1 Key principles 8
  - 2.1.1 Consistency 9
  - 2.1.2 Robustness 9
  - 2.1.3 Comprehensiveness 9
  - 2.1.4 Comparability and future proofing 9
- 2.2. Defining urban areas and their centres 9
  - 2.2.1 Urban areas 9
  - 2.2.2 Urban area centres 9
- 2.3. Connectivity indicators 10
  - 2.3.1. Defining connectivity for each of the three target spatial levels 10
  - 2.3.2 Using accessibility to measure connectivity 10
  - 2.3.3 Indicators by transport mode and time of day 11
  - 2.3.4 Normalisation 11
- 2.4. List of connectivity indicators 11
- 2.5. Demand representation 17
  - 2.5.1. Weighting by residential population 17
  - 2.5.2. Weighting by jobs 17
- 2.6. Infrastructure representation 17
- 2.7. Limitations of the adopted approach 18
  - 2.7.1. Over-reliance on BUA centres 18
  - 2.7.2. Impact of capacity and travel cost 18

3. Conclusion 19

Appendix 1: Defining built-up areas (BUA) 20

Appendix 2: Defining BUA centres 21
- A2.1. Calculating transport costs to multiple BUA-centre OAs 21
- A2.3. Centre definitions for other geographies 21

Appendix 3: Estimating demand 23
- A3.1. Estimating residential population 23
- A3.2. Estimating workplace population 23
- A3.3. Representation of demand for international gateways 24

Appendix 4: The multimodal transport network 24
- A4.1. Structure 24
- A4.2. Modelling capabilities 25

A4.3. Network Data 25
A4.4. Mapping locations on the road network 25
A4.5. Road Traffic Data 26
A4.6. Comparability with future versions 26
A4.7. Comparability with the previous (2016) version 27

Appendix 5: Centre for Cities lookup table 28

Appendix 6: Impact of distance and normalisation 31
A6.1. Values 31
A6.2. Normalisation 31
A6.3. Sensitivity analysis 31

Appendix 7: Relationship between accessibility and speed of travel 32
A7.1 Introduction 32
A7.2 Proving the relationship 32
A7.3 Limitations of use 33
A7.4 Average speeds of travel outputs 34
A7.4.1 Flow average speeds 34
A7.4.2 Time average speeds 34

Appendix 8: Connectivity Database Schema 35
origin_type 35
origin_id 35
origin_name 35
origin_residential_population 35
origin_workplace_population 35
transport_mode 35
destination_type 36
demand_type 36
raw_accessibility 36
crow_fly_accessibility 37
normalised_accessibility 37
flow_avg_speed 37
time_avg_speed 37
pua 37

Appendix 9: Transport connectivity and productivity 38
A9.1 Introduction 38
A9.2 Methodology 38
A9.3 Results 40
A9.3.1 Accessibilities 41
A9.3.2 Normalised Accessibilities 42
A9.3.3 Flow-average speeds 43
A9.4 Conclusion 43

References 44

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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 the following spatial levels:

1. Within Built-up Areas[1] (BUAs): this provides connectivity metrics for each BUA in Great Britain, as measured by the speed of travel by private or public transport between each point in the BUA and its centre (centre of economic activity). The connectivity metrics are also calculated individually for each of the BUA's Sub-Divisions (i.e. between each point in each of the BUASD and the BUA's centre of economic activity).

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

3. Between Built-up Areas and international gateways (main ports, airports and the Channel Tunnel): this provides connectivity metrics for each BUA in Great Britain, as measured by the speed of travel by private or public transport between its centre and international gateways. These include Great Britain's main ports and airports and the Channel Tunnel.

4. Aggregate connectivity metrics have also been calculated at the levels of several administrative and statistical geographies: Regions, Counties, Local Authority Districts (LAD), Combined Local Authorities, and Travel to Work Areas (TTWA). For each geography the aggregate connectivity metrics have been calculated as the population-weighted averages of the disaggregate connectivity metrics of the BUASDs within this geography.

5. **Finally, connectivity metrics have been calculated between each international gateway** (main ports, airports and the Channel Tunnel) and any other point in Great Britain. At this stage, these metrics should be treated as experimental.

We use observed data, state-of-the-art transport modelling and economic theory to derive these indicators. For each BUA centre we calculate its accessibility for each transport mode and demand type. This includes connectivity indicators for (i) private transport off-peak time, (ii) private transport peak time, (iii) road public transport (including bus and coach), (iv) rail public transport, (v) all public transport (including bus, coach and rail) and (vi) the minimum travel time across all transport modes. All connectivity indicators are developed for 2022.

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.

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[1] And other reference geographies including Local Authority Districts, Combined Authorities, Counties, Regions, Travel to Work Areas and Built-up Area Subdivisions.

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 Built-up Areas, 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 several different spatial levels:

1. Within BUAs: this provides connectivity metrics for each built-up area (BUAs please see 4 below for other reference geographies[2]) 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. Moreover, for each BUA subdivision (BUASD) we calculate its connectivity to the activity centre of the BUA it belongs to.

2. Between BUAs and other locations: this provides connectivity metrics for each built-up area (please see 4 below for other reference geographies) and its sub-divisions (Census 2011 BUASDs), 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 2011 Census, as per the ONS/NRS definition.

3. Between BUAs and international gateways: 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 the main ports and airports in the UK.

4. Aggregate connectivity metrics are also provided for several levels of administrative and statistical geographies: Regions, Counties, Local Authority Districts (LAD), Combined Local Authorities, and Travel to Work Areas (TTWA). For each geography the aggregate connectivity metrics have been calculated as the population-weighted averages of the disaggregate connectivity metrics of the BUASDs within this geography.

5. **Finally, connectivity metrics have been calculated between each international gateway** (main ports, airports and the Channel Tunnel) and any other point in Great Britain. At this stage, these metrics should be treated as experimental.

The proposed connectivity indicators can be used to provide a meaningful assessment of the performance of Great Britain'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).

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] Including Local Authority Districts, Combined Authorities, Counties, Regions, and Travel to Work Areas (TTWAs).

2.1.1 Consistency

We use a consistent approach grounded in contemporary spatial interaction theory and transport demand analysis to construct indicators at all spatial levels. For all 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 indicators for each of the target spatial levels.

This includes connectivity indicators for (i) private transport off-peak time, (ii) private transport peak time, (iii) road public transport (including bus/coach and walk as required), (iv) rail public transport (rail and bus/walk as required), (v) public transport (including bus, coach and rail) and (vi) the minimum travel time across all transport modes.

2.1.4 Comparability and future proofing

All connectivity indicators are developed for 2022. Details on data sources for both years are 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 urban areas and their centres

To produce connectivity metrics for urban areas across Great Britain we require a predefined set of urban areas, and a method for defining their boundaries and their centres of economic activity.

2.2.1 Urban areas

To generate a set of urban areas 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 Urban area centres

We define the 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 centre of economic activity, the set of 2011 Census Output Areas (OAs) which present the highest job density in 2019 (details on how 2019 employment at the OA level is estimated are provided in appendix A3.2) expressed as:

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

Appendices 1, 2 and 3 detail the methodology used to define Built-Up Areas (BUA) and BUA centres across the UK.

2.3. Connectivity indicators

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

1. For the "within BUA[3]" (**intra**) set of indicators we calculate the connectivity of the centre of a Built-up Area as its connectivity (by transport mode) to all destinations within the boundaries of the BUA weighted by demand and travel time. Moreover, for each BUA subdivision (BUASD) we calculate its connectivity to the activity centre of the BUA it belongs to.
2. For the "between BUAs and other locations" (**inter**) set of indicators we calculate the connectivity of an activity centre of each BUA and BUASD as its connectivity (by transport mode) to all other destinations across the UK (destinations outside the BUA's boundary) weighted by demand and travel time.
3. We also provide a simple (**total**) indicator for which we calculate the connectivity of the centre of a BUA as its connectivity (by transport mode) to all other destinations across the UK weighted by demand and travel time.
4. For the set of indicators to Ports/Airports and the Channel Tunnel we calculate the connectivity of the centre of a BUA to each individual International Gateway.
5. We have also calculated aggregate connectivity metrics for several administrative and statistical geographies. These include Regions (GOR), Counties, Local Authority Districts (LAD), Combined Local Authorities, and Travel to Work Areas (TTWA). For each of these geographies we have calculated the aggregate connectivity metrics as the population-weighted averages of the disaggregate connectivity metrics of the BUASDs within this geography; i.e. for each of the BUASDs within the reference geography we calculate its inta-urban and inter-urban connectivity metrics and then we aggregate these metrics at the level of the reference geography by weighting them by the residential population of the BUASDs and calculating the average.

On an experimental basis, we have also calculated these indicators for each International Gateway (main UK port, airport and the Channel Tunnel). For each international gateway we have calculated its connectivity (by transport mode) to all destinations in Great Britain weighted by demand and travel time.

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:

[3] and other reference geographies including Local Authority Districts, Combined Authorities, Counties, Regions, Travel to Work Areas and Built-up Area Subdivisions.

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

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 motor transport off-peak time, (ii) private motor transport peak time, (iii) road public transport (including bus/coach and walk as necessary), rail public transport (rail and walk/bus as necessary), and (v) all public transport (including bus, coach and rail). 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. List of connectivity indicators

The connectivity database provides accessibility indicators according to table 2.1. The schema of the database is provided in Appendix 8.

Table 2.1. List of all outputs by metric, period, transport mode and scope. All indicators are provided both for absolute and crow-fly normalised values.

Metric	Period	Reference Entity	Transport mode	Scope
Accessibility	2022	BUA	Car peak time	Total (population/employment)
Accessibility	2022	BUA	Car off-peak time	Total (population/employment)
Accessibility	2022	BUA	Road Public transport (plus walk)	Total (population/employment)
Accessibility	2022	BUA	Rail Public transport (plus Bus/Walk)	Total (population/employment)
Accessibility	2022	BUA	All Public transport	Total (population/employment)
Accessibility	2022	BUA	Crow-fly	Total (population/employment)
Accessibility	2022	BUA	Car peak time	Intra (population/employment)
Accessibility	2022	BUA	Car off-peak time	Intra (population/employment)
Accessibility	2022	BUA	Road Public transport (plus walk)	Intra (population/employment)
Accessibility	2022	BUA	Rail Public transport (plus Bus/Walk)	Intra (population/employment)
Accessibility	2022	BUA	All Public transport	Intra (population/employment)
Accessibility	2022	BUA	Crow-fly	Intra (population/employment)
Accessibility	2022	BUA	Car peak time	Inter (population/employment)
Accessibility	2022	BUA	Car off-peak time	Inter (population/employment)
Accessibility	2022	BUA	Road Public transport (plus walk)	Inter (population/employment)
Accessibility	2022	BUA	Rail Public transport (plus Bus/Walk)	Inter (population/employment)
Accessibility	2022	BUA	All Public transport	Inter (population/employment)
Accessibility	2022	BUA	Crow-fly	Inter (population/employment)
Accessibility	2022	BUASD (all OAs)	Car peak time	Parent BUA Centre (population/employment)
Accessibility	2022	BUASD (all OAs)	Car off-peak time	Parent BUA Centre (population/employment)
Accessibility	2022	BUASD (all OAs)	Road Public transport (plus walk)	Parent BUA Centre (population/employment)
Accessibility	2022	BUASD (all OAs)	Rail Public transport (plus Bus/Walk)	Parent BUA Centre (population/employment)
Accessibility	2022	BUASD (all OAs)	All Public transport	Parent BUA Centre (population/employment)
Accessibility	2022	BUASD (all OAs)	Crow-fly	Parent BUA Centre (population/employment)
Accessibility EXPERIMENTAL	2022	BUA	Car peak time	Ports/Airports/Channel Tunnel
Accessibility EXPERIMENTAL	2022	BUA	Car off-peak time	Ports/Airports/Channel Tunnel

Metric	Period	Reference Entity	Transport mode	Scope
Accessibility	2022	BUA	Car peak time	Total (population/employment)
Accessibility	2022	BUA	Car off-peak time	Total (population/employment)
Accessibility	2022	BUA	Road Public transport (plus walk)	Total (population/employment)
Accessibility	2022	BUA	Rail Public transport (plus Bus/Walk)	Total (population/employment)
Accessibility	2022	BUA	All Public transport	Total (population/employment)
Accessibility EXPERIMENTAL	2022	BUA	Road Public transport (plus walk)	Ports/Airports/Channel Tunnel
Accessibility EXPERIMENTAL	2022	BUA	Rail Public transport (plus Bus/Walk)	Ports/Airports/Channel Tunnel
Accessibility EXPERIMENTAL	2022	BUA	All Public transport	Ports/Airports/Channel Tunnel
Accessibility EXPERIMENTAL	2022	BUA	Crow-fly	Ports/Airports/Channel Tunnel
Accessibility	2022	BUASD	Car peak time	Inter (outside parent BUA) (population/employment)
Accessibility	2022	BUASD	Car off-peak time	Inter (outside parent BUA) (population/employment)
Accessibility	2022	BUASD	Road Public transport (plus walk)	Inter (outside parent BUA) (population/employment)
Accessibility	2022	BUASD	Rail Public transport (plus Bus/Walk)	Inter (outside parent BUA) (population/employment)
Accessibility	2022	BUASD	All Public transport	Inter (outside parent BUA) (population/employment)
Accessibility	2022	BUASD	Crow-fly	Inter (outside parent BUA) (population/employment)
Accessibility	2022	LAD/Combined Authority/County	Car peak time	Total (population/employment)
Accessibility	2022	LAD/Combined Authority/County	Car off-peak time	Total (population/employment)
Accessibility	2022	LAD/Combined Authority/County	Road Public transport (plus walk)	Total (population/employment)
Accessibility	2022	LAD/Combined Authority/County	Rail Public transport (plus Bus/Walk)	Total (population/employment)
Accessibility	2022	LAD/Combined Authority/County	All Public transport	Total (population/employment)
Accessibility	2022	LAD/Combined Authority/County	Crow-fly	Total (population/employment)
Accessibility	2022	LAD/Combined Authority/County	Car peak time	Intra (population/employment)

Accessibility	2022	LAD/Combined Authority/County	Car off-peak time	Intra (population/employment)
Accessibility	2022	LAD/Combined Authority/County	Road Public transport (plus walk)	Intra (population/employment)
Accessibility	2022	LAD/Combined Authority/County	Rail Public transport (plus Bus/Walk)	Intra (population/employment)
Accessibility	2022	LAD/Combined Authority/County	All Public transport	Intra (population/employment)
Accessibility	2022	LAD/Combined Authority/County	Crow-fly	Intra (population/employment)
Accessibility	2022	LAD/Combined Authority/County	Car peak time	Inter (population/employment)
Accessibility	2022	LAD/Combined Authority/County	Car off-peak time	Inter (population/employment)
Accessibility	2022	LAD/Combined Authority/County	Road Public transport (plus walk)	Inter (population/employment)
Accessibility	2022	LAD/Combined Authority/County	Rail Public transport (plus Bus/Walk)	Inter (population/employment)
Accessibility	2022	LAD/Combined Authority/County	All Public transport	Inter (population/employment)
Accessibility	2022	LAD/Combined Authority/County	Crow-fly	Inter (population/employment)
Accessibility EXPERIMENTAL	2022	LAD/Combined Authority/County	Car peak time	Ports/Airports/Channel Tunnel
Accessibility EXPERIMENTAL	2022	LAD/Combined Authority/County	Car off-peak time	Ports/Airports/Channel Tunnel
Accessibility EXPERIMENTAL	2022	LAD/Combined Authority/County	Road Public transport (plus walk)	Ports/Airports/Channel Tunnel
Accessibility EXPERIMENTAL	2022	LAD/Combined Authority/County	Rail Public transport (plus Bus/Walk)	Ports/Airports/Channel Tunnel
Accessibility EXPERIMENTAL	2022	LAD/Combined Authority/County	All Public transport	Ports/Airports/Channel Tunnel
Accessibility EXPERIMENTAL	2022	LAD/Combined Authority/County	Crow-fly	Ports/Airports/Channel Tunnel

Accessibility	2022	Region/Scotland/ Wales	Car peak time	Total (population/employment)
Accessibility	2022	Region/Scotland/ Wales	Car off-peak time	Total (population/employment)
Accessibility	2022	Region/Scotland/ Wales	Road Public transport (plus walk)	Total (population/employment)
Accessibility	2022	Region/Scotland/ Wales	Rail Public transport (plus Bus/Walk)	Total (population/employment)
Accessibility	2022	Region/Scotland/	All Public transport	Total (population/employment)

		Wales		
Accessibility	2022	Region/Scotland/ Wales	Crow-fly	Total (population/employment)
Accessibility	2022	Region/Scotland/ Wales	Car peak time	Intra (population/employment)
Accessibility	2022	Region/Scotland/ Wales	Car off-peak time	Intra (population/employment)
Accessibility	2022	Region/Scotland/ Wales	Road Public transport (plus walk)	Intra (population/employment)
Accessibility	2022	Region/Scotland/ Wales	Rail Public transport (plus Bus/Walk)	Intra (population/employment)
Accessibility	2022	Region/Scotland/ Wales	All Public transport	Intra (population/employment)
Accessibility	2022	Region/Scotland/ Wales	Crow-fly	Intra (population/employment)
Accessibility	2022	Region/Scotland/ Wales	Car peak time	Inter (population/employment)
Accessibility	2022	Region/Scotland/ Wales	Car off-peak time	Inter (population/employment)
Accessibility	2022	Region/Scotland/ Wales	Road Public transport (plus walk)	Inter (population/employment)
Accessibility	2022	Region/Scotland/ Wales	Rail Public transport (plus Bus/Walk)	Inter (population/employment)
Accessibility	2022	Region/Scotland/ Wales	All Public transport	Inter (population/employment)
Accessibility	2022	Region/Scotland/ Wales	Crow-fly	Inter (population/employment)
Accessibility EXPERIMENTAL	2022	Region/Scotland/ Wales	Car peak time	Ports/Airports/Channel Tunnel
Accessibility EXPERIMENTAL	2022	Region/Scotland/ Wales	Car off-peak time	Ports/Airports/Channel Tunnel
Accessibility EXPERIMENTAL	2022	Region/Scotland/ Wales	Road Public transport (plus walk)	Ports/Airports/Channel Tunnel
Accessibility EXPERIMENTAL	2022	Region/Scotland/ Wales	Rail Public transport (plus Bus/Walk)	Ports/Airports/Channel Tunnel
Accessibility EXPERIMENTAL	2022	Region/Scotland/ Wales	All Public transport	Ports/Airports/Channel Tunnel
Accessibility EXPERIMENTAL	2022	Region/Scotland/ Wales	Crow-fly	Ports/Airports/Channel Tunnel

Accessibility	2022	TTWA	Car peak time	Total (population/employment)
Accessibility	2022	TTWA	Car off-peak time	Total (population/employment)
Accessibility	2022	TTWA	Road Public transport (plus walk)	Total (population/employment)

Accessibility	2022	TTWA	Rail Public transport (plus Bus/Walk)	Total (population/employment)
Accessibility	2022	TTWA	All Public transport	Total (population/employment)
Accessibility	2022	TTWA	Minimum travel time	Total (population/employment)
Accessibility	2022	TTWA	Crow-fly	Total (population/employment)
Accessibility	2022	TTWA	Car peak time	Intra (population/employment)
Accessibility	2022	TTWA	Car off-peak time	Intra (population/employment)
Accessibility	2022	TTWA	Road Public transport (plus walk)	Intra (population/employment)
Accessibility	2022	TTWA	Rail Public transport (plus Bus/Walk)	Intra (population/employment)
Accessibility	2022	TTWA	All Public transport	Intra (population/employment)
Accessibility	2022	TTWA	Crow-fly	Intra (population/employment)
Accessibility	2022	TTWA	Car peak time	Inter (population/employment)
Accessibility	2022	TTWA	Car off-peak time	Inter (population/employment)
Accessibility	2022	TTWA	Road Public transport (plus walk)	Inter (population/employment)
Accessibility	2022	TTWA	Rail Public transport (plus Bus/Walk)	Inter (population/employment)
Accessibility	2022	TTWA	All Public transport	Inter (population/employment)
Accessibility	2022	TTWA	Minimum travel time	Inter (population/employment)
Accessibility	2022	TTWA	Crow-fly	Inter (population/employment)
Accessibility EXPERIMENTAL	2022	TTWA	Car peak time	Ports/Airports/Channel Tunnel
Accessibility EXPERIMENTAL	2022	TTWA	Car off-peak time	Ports/Airports/Channel Tunnel
Accessibility EXPERIMENTAL	2022	TTWA	Road Public transport (plus walk)	Ports/Airports/Channel Tunnel
Accessibility EXPERIMENTAL	2022	TTWA	Rail Public transport (plus Bus/Walk)	Ports/Airports/Channel Tunnel
Accessibility EXPERIMENTAL	2022	TTWA	All Public transport	Ports/Airports/Channel Tunnel
Accessibility EXPERIMENTAL	2022	TTWA	Crow-fly	Ports/Airports/Channel Tunnel

Accessibility EXPERIMENTAL	2022	Ports/Airports/Channel Tunnel	Car peak time	Total (population/employment)
Accessibility EXPERIMENTAL	2022	Ports/Airports/Channel Tunnel	Car off-peak time	Total (population/employment)
Accessibility EXPERIMENTAL	2022	Ports/Airports/Channel Tunnel	Road Public transport (plus walk)	Total (population/employment)
Accessibility EXPERIMENTAL	2022	Ports/Airports/Cha	Rail Public transport (plus	Total (population/employment)

		nnel Tunnel	Bus/Walk)	
Accessibility EXPERIMENTAL	2022	Ports/Airports/Channel Tunnel	All Public transport	Total (population/employment)
Accessibility EXPERIMENTAL	2022	Ports/Airports/Channel Tunnel	Crow-fly	Total (population/employment)

2.5. 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).

2.5.1. 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.

2.5.2. 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.

2.6. 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.

2.7. Limitations of the adopted approach

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

2.7.1. Over-reliance on BUA 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.

2.7.2. Impact of capacity and travel cost

The proposed approach avoids translating 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. 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 BUA 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 BUA 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 BUA[4], 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).

[4] The method of calculating these contributions is provided in Appendix 3, relies only on open-access data and can easily be reproduced by 3rd parties.

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.

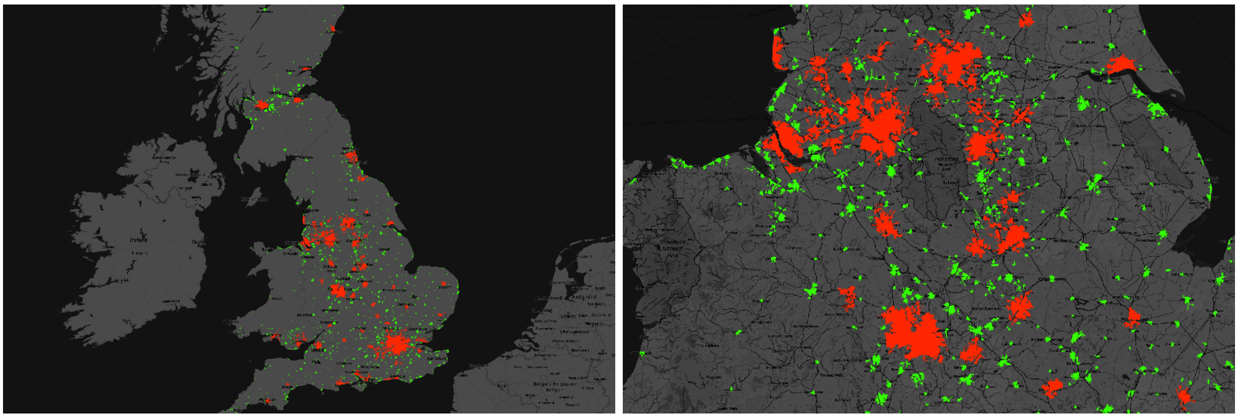

Figure 15. 1000 largest GB settlements (2011 population). Red colour: Primary Urban Areas (PUA) according to the Centre for Cities. Boundaries based on Office for National Statistics 2011 Built-up Areas and National Records of Scotland Settlements 2012.

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 BUA centres

We define the 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 centre of economic activity (city centre), the set of 2011 Census Output Areas (OAs) which present the highest job density expressed as:

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

To estimate the workplace employment in each Census OA, we use 2019 BRES; for details on the method used please see A3.2 (Estimating workplace population). Each OA is ranked according to its *centrality score* in relation to the rest of the OAs inside the same BUA.

The BUA centre is defined as the set of OAs with *centrality score* equal or higher than or equal to 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 BUA-centre OAs

When a Built-Up Area (BUA) has more than 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.

A2.3. Centre definitions for other geographies

As part of the 2022 connectivity analysis, connectivity metrics are calculated for the following types of geographies:

1. Built-Up Areas (BUA)
2. BUA Sub Divisions (Localities for Scotland) (BUASD)

   (Connectivities for the BUASD centres are only used to calculate aggregate connectivity values for 3 to 7 below and are not available in the database)
3. Local Authority Districts (LAD)
4. Counties
5. Combined Authorities
6. Regions
7. Travel To Work Areas (TTWA)
8. Ports (20 major ports)
9. Airports (20 major airports)
10. Le Shuttle

For each of the BUASDs we define the centre of economic activity in the same way we define it for BUAs; i.e. the set of OAs in the top 0.2% of OAs in the BUASD in terms of employment reach (within 15 mins walk from the OA). **These are only used to calculate aggregate connectivity values for 3 to 7 above and are not available in the database.**

For LADs, Counties, Combined Authorities, Regions and TTWAs the accessibility metrics are based on the weighted average of the accessibilities of the BUASDs (point 2 in the list above) located fully within them, where weights are the total residential population of each BUASD.

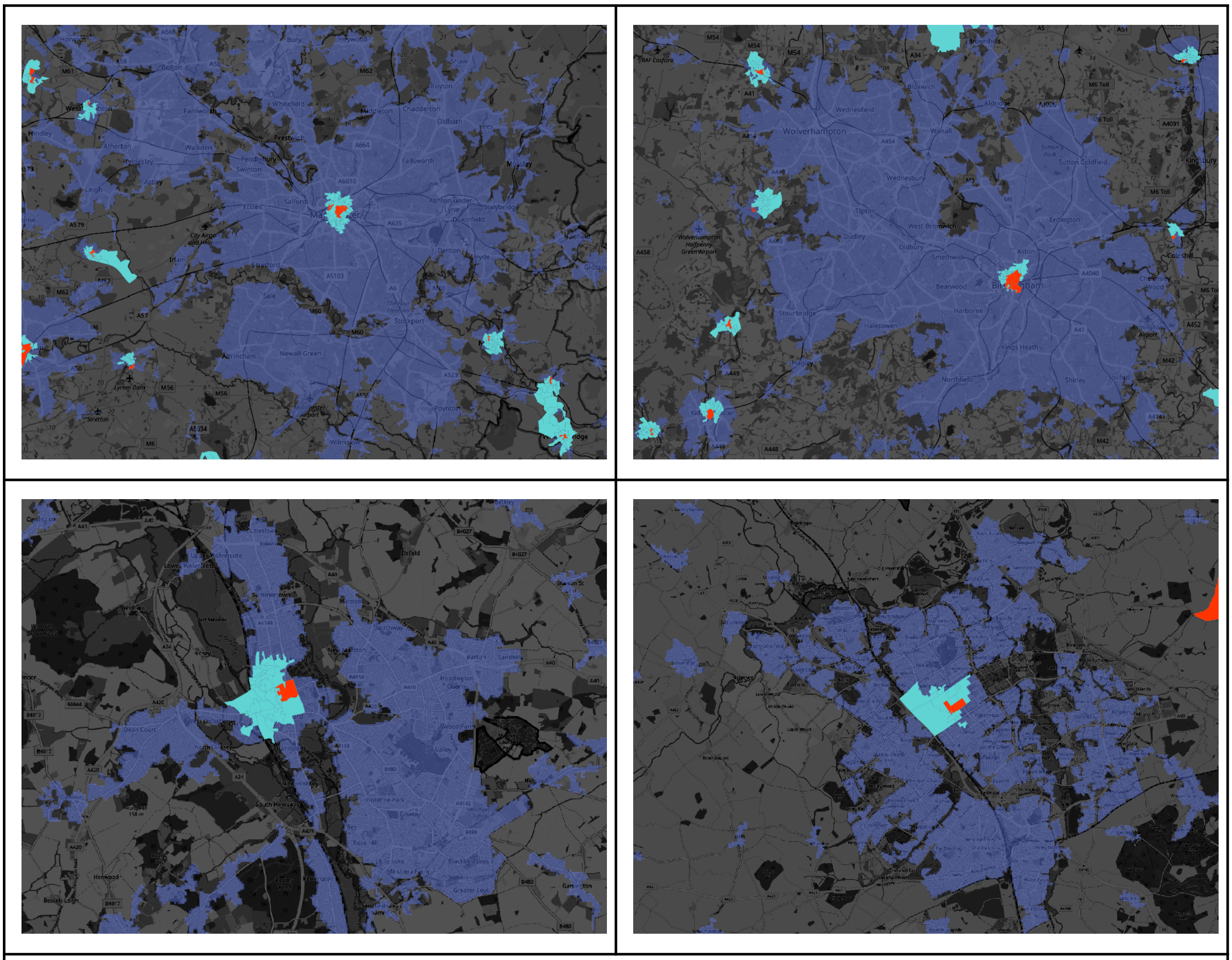

Figure 16. City centre size. All employment within 15 mins from city centre OAs by public transport | Red polygons: city centre, Cyan polygons: city centre reach, Blue polygons: city boundaries | Top left: Manchester, top right: Birmingham, bottom left: Oxford, bottom right: Milton Keynes

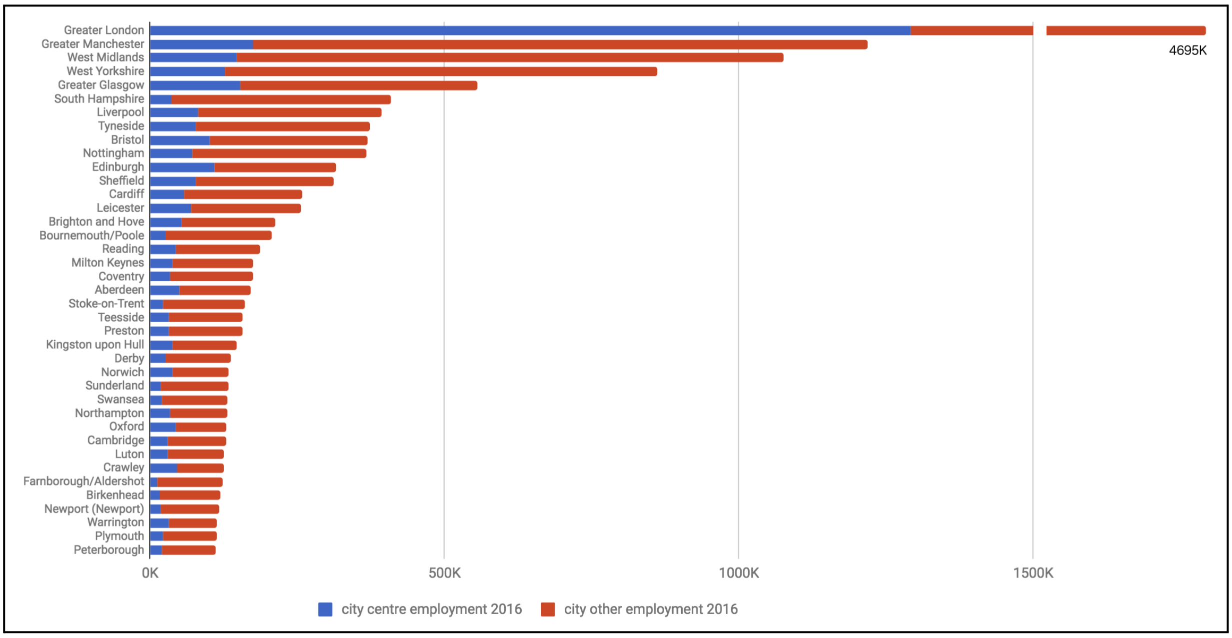

Figure 17. Comparing workplace employment within city centres (blue) and the rest of the built-up area (red).

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

To estimate the current resident population we use the latest releases (mid-2020) 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 at the LSOA/Scottish Data Zones level. We use the 2011 resident population Census table (KS101UKoa) to distribute the 2020 resident population estimates from the LSOA to the OA level.

A3.2. Estimating workplace population

To estimate the current workplace employment we use the 2019 Business Register and Employment Survey which provides job estimates by industry at the 2011 LSOA level for England and Wales and the 2011 Data Zones for Scotland. This includes employee and employment estimates for all sectors other than SIC01000 (farm agriculture). 2020 data is available but will not be used because of the impact of Covid-19 on workforce locations. We use the 2011 workplace employment Census (table WP101UKoa) to distribute the 2019 workplace employment estimates from the LSOA to the OA level.

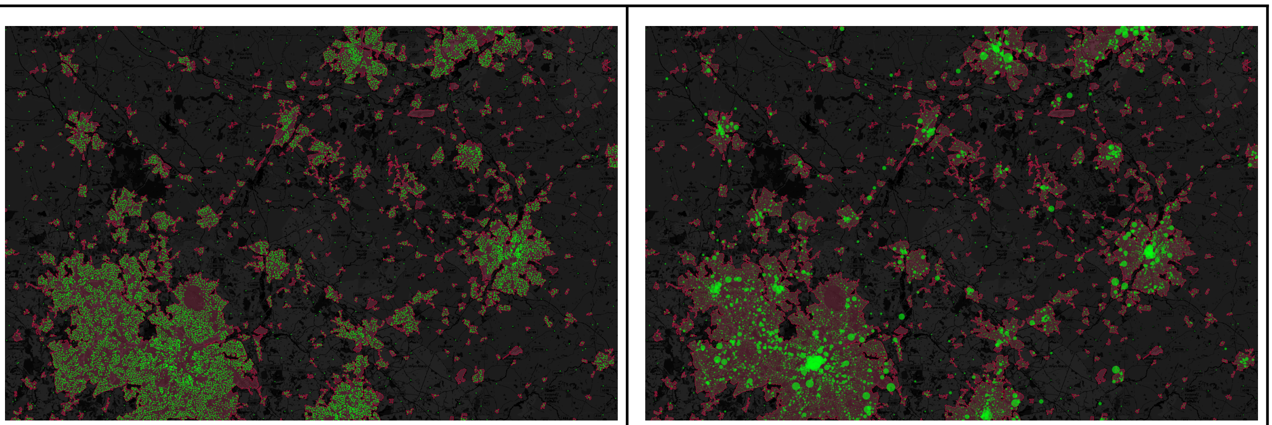

Figure 18. Left: 2011 Census Output Area (OA11) population-weighted centroids inside settlements used to define settlement city centres. Right: Workplace employment demand visualised using variable circle sizes for each OA11 centroid.

A3.3. Representation of demand for international gateways

When calculating the accessibility of BUAs and other reference geographies to International Ports, Airports and for Le Shuttle, the demand associated with each of the international gateways is equal to 1.0; i.e. the relative impact of each international gateway to the calculated accessibility of the reference geography is equal. Because of this, the international gateway connectivity results should be considered experimental.

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/light railway 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.).

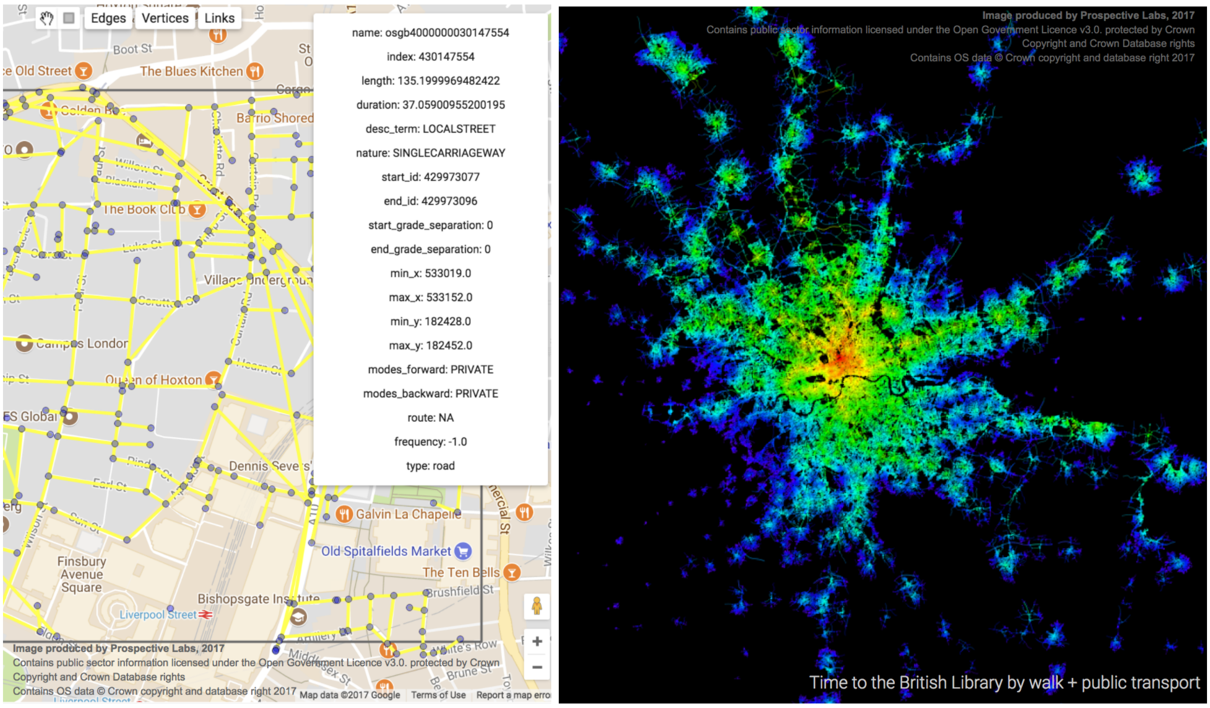

Figure 19. Prospective's multimodal transport network: A spatio-temporal granular representation of all the entities which make up a multimodal transport infrastructure

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. Network Data

The UK multimodal network is based on data from the following sources: OpenStreetMap (road network and routing information, updated monthly), Travelline (bus, coach, tram, and light rail timetable data - updated weekly), The Rail Delivery Group (rail timetable data - updated weekly).

A4.4. Mapping locations on the road network

Each OA (Output Area) centroid and other locations, such as the ports and airports where mapped to a single point on the road network. In the case of OAs, where available (e.g. in England and Wales) population weighted centroids were used. Each port/airport was represented by a single coordinate (lat/lon); this coordinate was mapped to its closest point on the road network. All travel times and distances used in the connectivity analysis are based on these points. We consider that this spatial approximation is sufficient for the type of connectivity analysis performed in this study.

A4.5. Road Traffic Data

Achievable peak and off-peak motor traffic speeds for each road segment in the road network are estimated using vehicle GPS trajectory data from two sources:

1. The Bus Open Data Service (BODS - www.bus-data.dft.gov.uk/)
2. The Live traffic information Service (webtris.highwaysengland.co.uk) from Highways England

In the case of BODS Siri-VM and Timetable data of all available bus services in England, Wales and Scotland was collected for a period of 2 weeks in February 2022. The Siri-VM data was linked to the Timetable data and the combined data used to generate bus-route geometries. These geometries and the original Siri-VM data was mapmatched on the OpenStreetMap road model and used to estimate the average travel speed of each segment of each bus route by time of day. Using the route geometries these speeds were linked to individual road segments of the network and used to estimate representative motor traffic speeds for each road segment by time of day (after filtering out road segments close to bus stops and any parts of the network with dedicated bus lanes and applying any required speed conversion factors).

In the case of WebTRIS data (Highways England) data was collected in December 2021 and was map-matched on the OpenStreetMap road model and used to estimate the average travel speed in the Motorway and A-road road network by time of day. The BODS- and WebTRIS-generated road segment speed estimates were combined to create the full set of traffic-speed estimates for the whole of Great Britain. The set of road segments for which BODS- and WebTRIS- generated speed estimates were available was used to evaluate the level of relative bias between the two types of estimates. The results of the analysis showed that no significant systematic relative bias was present. The full set of traffic-speed estimates for Great Britain covered more than 1% of the total number of road links in the road network, representing more than 2% of the total road length and - an estimated- 5-10% of the total daily traffic in Great Britain. In the case of the Motorway and A-road network coverage was significantly higher.

The full set of traffic-speed estimates was used to develop a parametric model of road-traffic speeds that was used to generate speed estimates for every road-segment in the road-network without direct speed estimates. The parameters used were the location of the road segment, the type of road, the setting (urban/rural), size of settlement and population and employment densities in the vicinity of the road segment. The resulting model performed very well for both peak (7-10am) and off-peak (7-10pm) speed estimates across the type of roads.

A4.6. Comparability with future versions

The use of two government-backed open-access databases means that the exact same methodologies for both data collection and speed estimation can be used in the future. As such, connectivity metrics derived using these will be directly comparable to the current version. For road segments for which direct observations are available both for the current version and any future version, a direct comparison of the state of average road speeds will be possible. We should note that this will include a large share of the Motorway and A-road links that carry heavy traffic flows and play a critical role in the connectivity performance of settlements. Having said that, the connectivity analysis that has been performed for this study relies on the full road network to provide road connectivity metrics and therefore it requires speed estimates for all road segments the speed estimates of the majority of which rely on a parametric speed estimation model. One of the parameters of this model is the location of the road segment but since other parameters come into play the speed estimates for each road segment are not necessarily representative of the relative state of the local road network compared with the state of other locations in Great Britain. As such, direct comparison of the evolution of the connectivity metrics for different settlements across time cannot be used to draw safe conclusions about how the state of the road traffic has changed over time.

A safer comparison would, however, be possible by comparing the evolution of the speeds for the subset of road segments in the vicinity of each settlement for which direct speed observations are available. Considering the very large coverage of the road network (more than 2% of its length covered with direct observations), this approach would allow the extraction of robust conclusions for large settlements, especially in England.

A4.7. Comparability with the previous (2016) version

It is important to note that the 2016 connectivity database relied exclusively on modelled speed estimates. This means that the speed estimates of all road segments in the 2016 road network model were predicted using a parametric model based on the type, length and the location of a road segment and the density of activity around it to estimate its peak speed. The sample road speeds that were collected and used to train and validate the 2016 speed prediction model were not used directly in the road network to calculate connectivities.

In the 2022 connectivity analysis, for road segments for which there is a sufficient number of speed observations, we use the average of these observations directly as the estimated speed for these road segments. Therefore, we only use a parametric predictive model (based on the type, length and the location of a road segment and the density of activity around it) to predict the speed of road segments for which we have no or very few speed observations.

The difference in approaches is demonstrated when comparing 2016 and 2022 inter-urban peak car connectivities. This is because the inter-urban car connectivity of many of the BUAs are affected by the road speeds of axial motorways that service them. In 2016 the speeds of these motorways were based on the 2016 parametric speed model. In 2022 the speeds of the majority of motorways are directly based on observations.

Moreover, in the 2016 connectivity database, the off-peak car connectivity metrics were based on free-flow speeds (i.e. the legal max driving speed for each road segment). In the 2022 connectivity database, the off-peak car connectivity metrics are based on observed and model speed estimates for the 7-10pm time period of typical weekdays in February/March 2022. This means that the observed traffic delays during these times are reflected in the calculated connectivity metrics.

Finally, the 2016 connectivity values for public transport were based on simpler estimated walk and wait times, particularly in the case of major rail stations. Therefore in some cases the 2016 connectivity metrics are likely to be marginally over-estimating the public transport connectivity of places that rely on rail legs from major rail stations.

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	Centre for Cities Primary Urban Area (PUA) name(s)
E34004707	Greater London BUA	London
E34005054	Greater Manchester BUA	Manchester
E34005001	West Midlands BUA	Birmingham
E34004684	West Yorkshire BUA	Leeds, Bradford, Huddersfield, Wakefield
S20000732	Greater Glasgow	Glasgow
E34004977	South Hampshire BUA	Portsmouth, Southampton
E34004801	Liverpool BUA	Liverpool
E34004998	Tyneside BUA	Newcastle
E34004946	Nottingham BUA	Nottingham
E34004969	Sheffield BUA	Sheffield
E34004965	Bristol BUA	Bristol
E34004647	Leicester BUA	Leicester
S20000682	Edinburgh	Edinburgh
E34004748	Brighton and Hove BUA	Brighton, Worthing
E34005031	Bournemouth/Poole BUA	Bournemouth
W37000384	Cardiff BUA	Cardiff
E34004855	Coventry BUA	Coventry
E34004802	Teesside BUA	Middlesbrough
E34004612	Stoke-on-Trent BUA	Stoke
E34004630	Sunderland BUA	Sunderland
E34004640	Reading BUA	Reading
E34004654	Birkenhead BUA	Birkenhead
E34005039	Preston BUA	Preston
E34004839	Kingston upon Hull BUA	Hull
W37000385	Newport (Newport) BUA	Newport
E34005046	Southend-on-Sea BUA	Southend
W37000427	Swansea BUA	Swansea
E34004638	Derby BUA	Derby
E34004983	Luton BUA	Luton
E34005012	Plymouth BUA	Plymouth

E34004885	Farnborough/Aldershot BUA	Aldershot
E34005040	Medway Towns BUA	Chatham
E34005056	Milton Keynes BUA	Milton Keynes
E34004900	Blackpool BUA	Blackpool
E34004869	Barnsley/Dearne Valley BUA	Barnsley
E34004611	Northampton BUA	Northampton
E34004893	Norwich BUA	Norwich
S20000504	Aberdeen	Aberdeen
E34004828	Swindon BUA	Swindon
E34004880	Crawley BUA	Crawley
E34004730	Ipswich BUA	Ipswich
E34004572	Oxford BUA	Oxford
E34004959	Wigan BUA	Wigan
E34004765	Mansfield BUA	Mansfield
E34004715	Peterborough BUA	Peterborough
E34004940	Slough BUA	Slough
E34004251	Warrington BUA	Warrington
E34004798	Cambridge BUA	Cambridge
E34005036	York BUA	York
E34004696	Doncaster BUA	Doncaster
E34004693	Gloucester BUA	Gloucester
S20000665	Dundee	Dundee
E34004645	Basildon BUA	Basildon
E34004622	Telford BUA	Telford
E34004743	Burnley BUA	Burnley
E34004557	Blackburn BUA	Blackburn
E34004704	High Wycombe BUA	-
E34004625	Hastings BUA	-
E34005048	Colchester BUA	-
E34004917	Grimsby BUA	-
E34004846	Thanet BUA	-
E34004858	Exeter BUA	Exeter
E34004970	Burton upon Trent BUA	-
S20000864	Motherwell and Bellshill	-
E34004905	Accrington/Rossendale BUA	-

E34004862	Eastbourne BUA	-
E34005030	Lincoln BUA	-
E34004813	Paignton/Torquay BUA	-
E34003710	Cheltenham BUA	-
E34004924	Chelmsford BUA	-
E34004399	Maidstone BUA	-
E34005009	Basingstoke BUA	-
E34004985	Chesterfield BUA	-
E34004993	Bedford BUA	-
E34004941	Worcester BUA	-
S20000693	Falkirk	-
E34004686	Lancaster/Morecambe BUA	-

Appendix 6: Impact of distance and normalisation

A6.1. Values

β_p represents that impact of distance/travel time on the attractiveness of city centre i to consumers in j. 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). Based on the 2017 National Travel Survey (DfT, https://www.gov.uk/government/statistics/national-travel-survey-2019), this is achieved for $\beta_p = 0.00099340379$.

A6.2. Normalisation

For the crow-fly accessibility calculations, β_p is set to represent equivalent average journey travel time under speed equal to 50 km/hr. This means that the crow-fly accessibility of a city-centre i represents a hypothetical scenario where every destination j can be reached from i by travelling in a straight line at 50km/h. Using crow-fly accessibilities to normalise all other accessibility metrics, means that the spatial distribution of destinations j around each city-centre can be controlled for and therefore the normalised accessibilities are reflective of the connectivity level of the existing road and public transport infrastructure.

A6.3. Sensitivity analysis

In order to establish the impact of the selected beta value on the relative connectivity levels of each settlement we performed a sensitivity analysis. We calculated the connectivity of each settlement (for car peak-time and for public transport) using half and double the original beta value and compared the resulting connectivity levels with the original values. The following table provides the correlation between the original residential and workplace connectivity values and the sensitivity test values. **Abs** represents the Pearson correlation coefficient in terms of the absolute connectivity values for the 1000 largest settlements in Great Britain. **Order** represents the Pearson correlation coefficient in terms of the connectivity order (based on normalised connectivity values) for the 1000 largest settlements in Great Britain. In all cases the correlation coefficients are very high, displaying low sensitivity of the overall result in terms of the exact value of the beta parameter in the accessibility model.

beta	transport_mode	residential connectivity (abs)	employment connectivity (abs)	normalised residential connectivity (order)	normalised employment connectivity (order)
half	car_peak	92%	91%	87%	83%
double	car_peak	88%	82%	86%	85%
half	public_transport	86%	81%	76%	79%
double	public_transport	83%	88%	78%	81%

Appendix 7: Relationship between accessibility and speed of travel

A7.1 Introduction

In order to improve the interpretability of the variation of accessibility between locations and transport modes we provide a relationship between accessibility a and average speed of travel s of a location p.

$a_2/a_1 = (s_2/s_1)^2$

The above relationship can be used to provide a speed-based interpretation of the accessibility differences between:

1. the normalised accessibilities of different locations with the same transport mode.
2. The normalised accessibilities of different transport modes for the same location.

In both these cases the relationship is intended to reflect average speed of travel between the location and all destinations from this location.

A7.2 Proving the relationship

In a two-dimensional continuous homogeneous plane, if x is distance, d is population density and s is the (constant) speed of travel, then the (unlimited horizon) accessibility a_p of location p is equal to:

$$a_{p\,(0\to+\infty)} = \int_0^{+\infty} ((2\pi x) \cdot d \cdot exp(-\beta \cdot x/s))dx$$

where $(2\pi x)$ is marginal area, $((2\pi x) \cdot d)$ is marginal population and (x/s) is travel time from location p. By solving the integral we get:

$$a_{p\,(x)} = \int((2\pi x) \cdot d \cdot exp(-\beta \cdot x/s))dx = -2\pi \cdot d \cdot s \cdot (\beta x + s) \cdot exp(\beta \cdot x/s)/\beta^2 + c$$

The limit of $a_{p\,(x)}$ as x approaches positive infinity is $\lim_{x\to+\infty} a_{p\,(x)} = 0$, so the accessibility a_p of location p is equal to:

$$a_{p\,(0\to+\infty)} = 2\pi \cdot d \cdot s^2/\beta^2 = 2\pi \cdot d \cdot (s/\beta)^2$$

Therefore, the relationship of the accessibilities $a_{p,1}$ and $a_{p,2}$ of location p under different speeds of travel s_1 and s_2 is:

$$a_{p,2}/a_{p,1} = (s_2/s_1)^2$$

And the relationship between speeds of travel s_1 and s_2 is: $s_2 = s_1 \times \sqrt{a_{p,2}/a_{p,1}}$

A7.3 Limitations of use

As mentioned in the A7.1, the relationship between accessibilities and speeds is intended to reflect average speed of travel between the location and all destinations from this location. For simplicity, the formula that expresses the relationship is derived within a **simplified two-dimensional continuous setting, where demand is distributed uniformly and achievable travel speeds are fixed across space**. To confirm the formula works outside these conditions we have tested the relationship in simulated settings with the following combined effects:

1. Randomly distributed granular demand, and
2. Travel speed profiles that vary with travel distance

In all these cases, the relationship between accessibilities and speeds remained within 5-10% of the one suggested by the formula, even in cases where the introduced before/after difference in speeds was high (for example, in cases where the updated speeds were below 60% and over 150% the original speeds).

The results of the above analysis suggest that it is suitable to use the relationship between speeds and accessibilities to provide a speed-based interpretation of variation of normalised accessibilities between transport modes and between locations. For example, if the normalised accessibility $a_{p,m}$ of location p is 10% higher than the normalised accessibility $a_{q,m}$ of location q for the same transport mode m, it is suitable to say that the average speed of travel in location p is 4.9% $(1.049 = \sqrt{1.1})$ higher than the average speed of travel in location q for transport mode m. Equally, if the normalised accessibility $a_{p,m}$ of transport mode m is 50% higher than the normalised accessibility $a_{p,n}$ of transport mode n for the same location p, it is suitable to say that in location p, the average speed of travel by transport mode m is 22.5% $(1.225 = \sqrt{1.5})$ higher than the average speed of travel by transport mode n.

On the other hand, the proposed relationship is not suitable for inferring differences in speeds between individual segments of the road network. We should highlight that since the proposed relationship links speed differences to accessibility differences, it necessarily reflects the combined impact of speed of travel across the whole road network in the vicinity of a location AND the directness of the connections of this location to other locations (weighted by residential/workplace population in each location).

A7.4 Average speeds of travel outputs

The relationship between accessibility and speeds above is derived in a simplified two-dimensional continuous setting, where demand is distributed uniformly. As such, it works reasonably well in cases where the demand is distributed continuously in space, such as in the case of the demand distributed in OAs (output areas) across Great Britain.

However, the formula fails to generate meaningful results in cases of single or sparsely distributed destinations (e.g. in the case of International Gateways or intra-urban connectivities of small BUAs). For this reason the connectivity database includes directly calculated speed estimates for each connectivity output (see Appendix 8 below). Specifically there are as follows.

A7.4.1 Flow average speeds

The flow-average speed of this origin for this transport_mode, destination_type and demand_type. It represents the expected (weighted) average speed of travel between origin i and any destination j and it is equal to:

$$u_i^{flow} = \sum_{j \in J} \left(x_{ij}/t_{m,ij}\right) \cdot w_{d,j} \cdot exp\left(-\ \beta \cdot t_{m,ij}\right) / \sum_{j \in J} w_{d,j} \cdot exp\left(-\ \beta \cdot t_{m,ij}\right)$$

A7.4.2 Time average speeds

The time-average speed of this origin for this transport_mode, destination_type and demand_type. It represents the average speed of travel across all travel from origin i to destinations j and it is equal to:

$$u_i^{time} = \sum_{j \in J} \left(x_{ij}\right) \cdot w_{d,j} \cdot exp\left(-\ \beta \cdot t_{m,ij}\right) / \sum_{j \in J} \left(t_{m,ij}\right) \cdot w_{d,j} \cdot exp\left(-\ \beta \cdot t_{m,ij}\right)$$

Both the Flow and Time Average speeds above are directly calculated and fully compatible with their corresponding connectivity metric. They are calculated in km/hr and can be divided by 50 km/hr to generate an index where 1.0 is equal to the crow-fly values (i.e. the crow-fly values for both types of speed definition is 50km/hr).

Appendix 8: Connectivity Database Schema

origin_type

Possible Values

1. BUA:	Census 2011 Built-up Area / Scottish Census settlement (From activity Centre 2011 Census Output Areas)
2. BUASD	Census 2011 Built-up Area Sub Division / Scottish Census locality (From activity Centre 2011 Census Output Areas)
3. BUASD_ALL	Census 2011 Built-up Area Sub Division / Scottish Census locality (From all 2011 Census Output Areas)
4. LAD:	Local Authority District
5. COUNTY:	County
6. REGION:	UK Region
7. CAUTH:	Combined Authority
8. TTWA:	Census 2011 Travel-To-Work-Area
9. IG_RAIL:	International Gateway - Rail
10. IG_PORT:	International Gateway - Port
11. IG_AIRPORT:	International Gateway - Airport

origin_id

The unique ID of the origin

origin_name

The name of the origin

origin_residential_population

The residential population of the origin in 2020 based on ONS mid-year population estimates

origin_workplace_population

The workplace population of the origin in 2019 based on BRES estimates

transport_mode

The set of transport modes used to calculate this connectivity value

Possible Values

1. car_peak:	Private Car journeys 7-10 am
2. car_off_peak:	Private Car journeys 8-11 pm
3. public_transport:	Walk and use of any public transport modes (including train, metro, tram, cable-car, bus and ferry)
4. rail_transport:	Walk and use of any rail-based public transport modes (including

		train, metro, tram and cable-car)
5.	bus_transport:	Walk and use of bus

destination_type

The type of destinations that were considered when calculating this connectivity value

Possible Values

1.	OA11_All:	All Census 2011 Output Areas
2.	OA11_Intra:	Census 2011 Output Areas inside the footprint of the Built-up area (BUA) this origin is associated with*.
3.	OA11_Inter:	Census 2011 Output Areas outside the footprint of the Built-up area (BUA) this origin is associated with*.
4.	OA11_Intra_BUA_Centre	Census 2011 Output Areas inside the centre of activity of the parent Built-up area (BUA) this origin BUASD is associated with.
5.	IG_PORT	International Gateway: Port - One of the 20 major Ports in GB
6.	IG_AIRPORT	International Gateway: Airport - One of the 20 major Airports in GB
7.	IG_RAIL	International Gateway: Rail - The Le Shuttle Eurotunnel terminal in Folkestone
8.	IG_ALL	Any of the the International Gateways (Ports/Airports/Le Shuttle)

demand_type

The type of population at the destination location used to weight its connectivity contribution

Possible Values

1.	residential_population:	The residential population of the destination in 2020 based on ONS mid-year population estimates
2.	workplace_population:	The workplace population of the origin in 2019 based on BRES estimates
3.	unweighted:	Each destination is assigned a weight equal to 1.0

raw_accessibility

The raw accessibility value of this origin for this transport_mode, destination_type and demand_type. This is based on:

$A_i = \sum_{j \in J} w_{d,j} \cdot exp\left(-\ \beta \cdot t_{m,ij}\right)$ where i is the origin, j is the destination, m is the transport_mode, d is the demand_type, $w_{d,j}$ is the level of demand of type d in j, $t_{m,ij}$ is the travel time from i to j with transport_mode m and β is the decay factor.

crow_fly_accessibility

The crow-fly accessibility value of this origin for this destination_type and demand_type. This is based on:

$A_i^{CF} = \sum_{j \in J} w_{d,j} \cdot exp(-\beta \cdot c_{ij})$ where i is the origin, j is the destination, d is the demand_type, $w_{d,j}$ is the level of demand of type d in j, c_{ij} is the travel time from i to j under a constant speed of 50km/h in a straight line from i to j and β is the decay factor.

normalised_accessibility

The normalised connectivity of this origin for this transport_mode, destination_type and demand_type is equal to $A_i^{NORM} = A_i / A_i^{CF}$

flow_avg_speed

The flow-average speed of this origin for this transport_mode, destination_type and demand_type. It represents the expected (weighted) average speed of travel between origin i and any destination j and it is equal to:

$$u_i^{flow} = \sum_{j \in J} (x_{ij}/t_{m,ij}) \cdot w_{d,j} \cdot exp(-\beta \cdot t_{m,ij}) / \sum_{j \in J} w_{d,j} \cdot exp(-\beta \cdot t_{m,ij})$$

time_avg_speed

The time-average speed of this origin for this transport_mode, destination_type and demand_type. It represents the average speed of travel across all travel from origin i to destinations j and it is equal to:

$$u_i^{time} = \sum_{j \in J} (x_{ij}) \cdot w_{d,j} \cdot exp(-\beta \cdot t_{m,ij}) / \sum_{j \in J} (t_{m,ij}) \cdot w_{d,j} \cdot exp(-\beta \cdot t_{m,ij})$$

pua

TRUE if the origin is of origin_type BUA and is a Primary Urban Area (PUA) according to the Centre for Cities, FALSE otherwise.

Appendix 9: Transport connectivity and productivity

A9.1 Introduction

The objective of this section is to explore links between the transport connectivity outcomes of this study and indicators of productivity. In particular, the focus of the analysis is on whether the spatial variation of the produced connectivity metrics provided is reflective of similar variations in productivity.

A detailed review of the role of transport connectivity in driving productivity is beyond the scope of this study. Briton Harris (2001) and more recently Littman (2022) provide high quality accounts on the definition, driving factors, and role of transport accessibility in planning, appraising and monitoring transport networks. Moreover, the relationship between transport connectivity and economic growth and productivity in particular is the subject of numerous studies. Two recent relevant studies are the one commissioned by the US National Academies of Sciences, Engineering, and Medicine (2014) and authored by a panel of international experts assessing the productivity impacts of transportation investments, and a evidence-based research study (Lee 2019) on the impact of transport infrastructure on productivity, employment growth and land values.

This section focuses on the analysis of the relationships between the connectivity metrics that we produce as part of this work and relevant productivity indicators. Any relationships between connectivity and productivity indicators are not presented here as evidence of causal link between the two and should not be used as such. The identification of clear causal mechanisms in these relationships is particularly hard and requires observations of the indicators at different points in time. Any established relationships are just accepted as reflective of the codependence of quality transport connectivity and high intensity of economic activity. High concentrations of economic activity typically generate pressure for investment in transport infrastructure and provide opportunities for financing them. Improvements in transport connectivity mean that more people can access these areas faster, reinforcing their competitive advantage. Therefore, any relationships between the two sets of indicators are path dependent, the product of a co-evolution across long periods of time. Successful interventions aiming to transform these landscapes are therefore likely to require sustained and targeted investment and careful continuous planning.

A9.2 Methodology

The connectivity indicators produced in this study focus on the accessibility of the activity centres of built-up areas (BUAs). In most cases, the activity centre of a BUA is defined by a small number of OAs. This means that we have been able to produce meaningful connectivity metrics for a very large number of cities and towns in Great Britain (around 1000), regardless of population size, with very high spatial fidelity of output connectivity metrics.

Part of the challenge in the analysis for this section has been producing productivity indicators at the same spatial resolution that makes the comparison between productivity and connectivity meaningful at the spatial resolution of the connectivity indicators (BUA centre of activity). Typical productivity data (e.g. GVA/full-time employee) is available at the national, regional or sub-regional levels but not at the spatial level required for this study. To address this, the analysis is based on proxy indicators of productivity. In particular we use:

1. Hourly and weekly earnings of full time employees as a measure of their productivity. This is based on the assumption that the labour cost / GVA ratio will be relatively stable across Great Britain. This assumption is not very strong considering the variations of the contribution of each SIC in total output by region but has been considered appropriate for the objectives of this study.
2. Annual rent rates / sq.m. for non-domestic/business activities. This is based on two assumptions: (i) the rent cost per unit of output and (ii) the square footage per employee remain relatively stable across Great Britain. In order to strengthen the assumptions, we break down rent rates by property type and focus on (a) office space, (b) small and medium size shops, (c) restaurants and similar food and beverage serving establishments.

For (1) we use the 2020 Annual Survey of Hours and Earnings (ONS). The data is output at the Parliamentary Constituency level and, for this study we used the ONS OA11-to-Constituency lookup table to associate each 2011 Output Area with hourly and weekly earnings per employee.

For (2) we use the 2017 VOA non-domestic rates entry-list (epoch 32) which provides the 2017 rateable values for all non-domestic properties active on mid-2022. The rateable value of a property is based on an assessment of the annual rent the property would provide if it was let on the open market at a fixed valuation date. We used the unadjusted rateable rate for each property that provides a £/sq.m. value for the property (without considering the particular state of the property).

These were aggregated to produce indicators for each BUA and BUASD in the connectivity database. The full list of proxy indicators for each geography (BUA and BUASD) includes:

1. Hourly Earnings per full time employee
2. Weekly Earnings per full time employee
3. Annual rent per sq.m of office space
4. Annual rent per sq.m of shop space
5. Annual rent per sq.m of restaurant space

To search for links between productivity and connectivity indicators we calculated Pearson correlation coefficient between the BUA and BUASD values of each of the indicators above and the connectivity metrics for these geographies broken down as follows:

1. Transport mode (car_peak, car_off_peak, public_transport, rail_transport, bus_transport)
2. Destination type (Intra, Inter, All, IG_Rail, IG_Port, IG_Airport, IG_All)
3. Demand type (residenttial_population, workplace_population, unweighted)
4. Primary Urban Area (true, false)

This analysis generated 700 combinations and for each we calculated the Pearson correlation coefficients for each of the following connectivity indicators:

1. Accessibility
2. Normalised Accessibility

3. Flow-average Speed

In the next subsection we present the results of this analysis.

A9.3 Results

We have filtered out all records with relative low correlation coefficients (below 0.65) and we only discuss the combinations with strong correlations between connectivity and productivity indicators. Based on the definition of the Pearson correlation coefficient r, a value of $r = 0.7$ means that 50% of the variation of one of the variables can be explained by the variation of the other indicator.

Figure A9.1 provides realisations of couples of random variables with different Pearson correlation coefficients, for illustrative purposes. All Pearson correlation coefficients in tables A9.1-4 are expressed as % to improve readability (e.g. 0.54 = 54%).

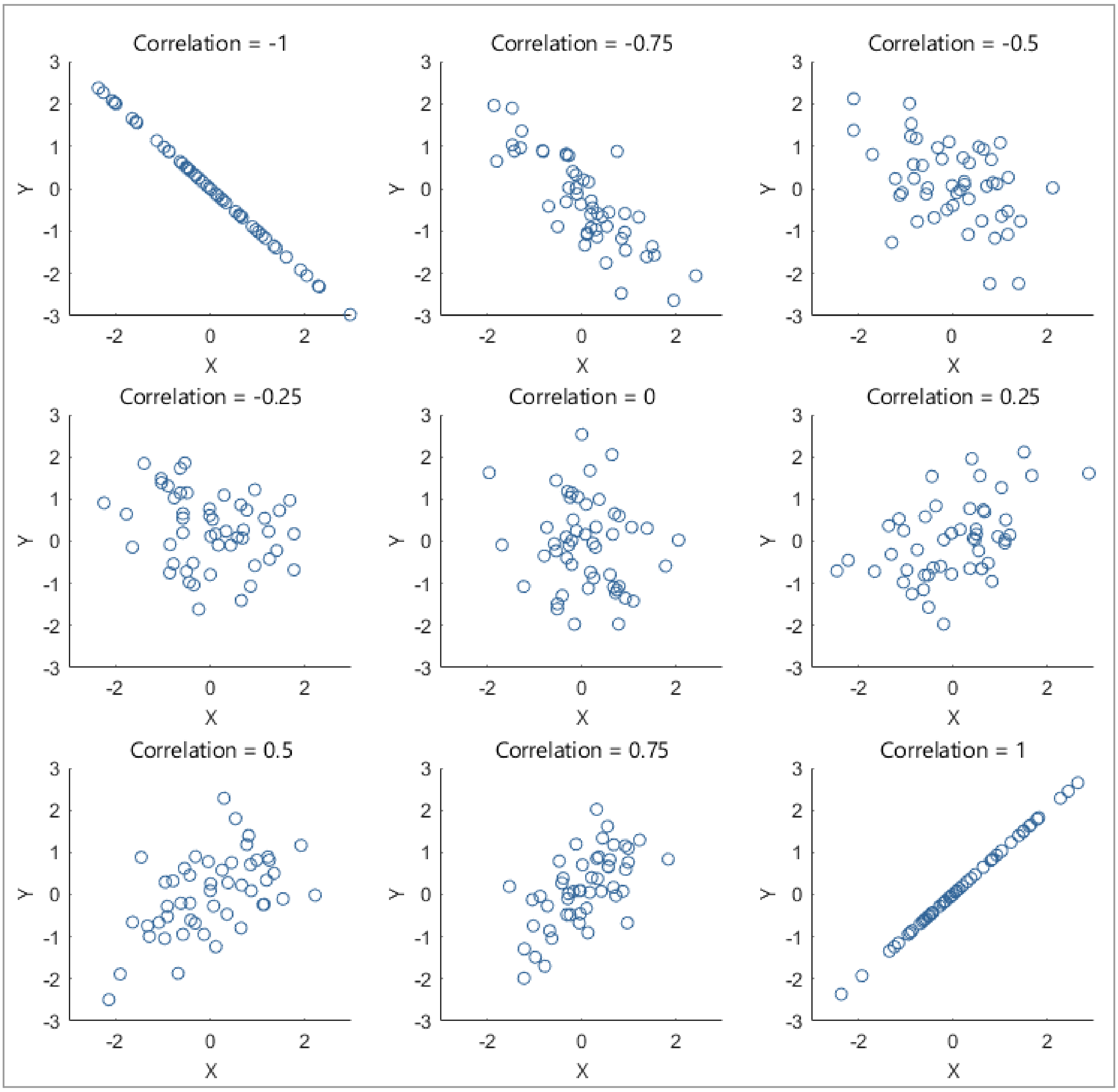

Figure A9.1: Realisations of couples of random variables X and Y with different Pearson correlation coefficients.

A9.3.1 Accessibilities

The first table presents all significant correlations between the accessibility (since this is not normalised it represents total accessible demand) values of geographies (BUA/BUASD) and the set of productivity indicators for all the destination types, demand types and transport modes.

The correlations between intra-urban BUA connectivity to residential population and retail rent-rates are particularly strong across all transport modes (with peak-car particularly strong). Equally strong is the relationship between intra-urban connectivity to residential population and the rents of food and drink premises, but in this case only for rail transport. In terms of the office rents, they are strongly correlated with both BUA and BUASD connectivities for rail transport and for BUASD they are also strong across the rest of the modes particularly for workplace connectivity.

	Origin type	BUA				BUASD		
	Destination type	OA11 All		OA11 Intra		IG ALL	OA11 Intra	
Productivity indicator	*Demand type*	Residential population	Workplace population	Residential population	Workplace population	unweighted	Residential population	Workplace population
Office rents	Car offpeak						68%	70%
	Car peak						67%	70%
	Public transport						67%	68%
	Rail			69%	69%	66%	71%	70%
Food-and-drink rents	Car offpeak						65%	65%
	Rail			75%	70%			
Retail rents	Bus	70%	73%	74%	73%			
	Car offpeak			74%	69%			
	Car peak			77%	71%			
	Public transport	71%	69%	73%	69%			
	Rail t	67%		73%				

Table A9.1

When we include the Primary Urban Area variable in the correlation analysis we get even stronger relationships between connectivity and productivity indicators for the primary urban areas (as defined by the Centre for Cities). These are particularly strong when looking at both the intra-urban and total connectivities of both the residential and the workplace population accessibilities for the rent-related productivity indicators (office, retail and food-and-drink rents).

There is also a weaker relationship between the earnings-based productivity indicators and total workplace connectivity indicator for car-based transport, indicating a link between well connected (in terms of road transport) large cities and high productivity.

	Origin type	BUA						BUASD		
	Destination type	IG ALL	IG RAIL	OA11 All		OA11 Intra		IG ALL	OA11 Intra	
Productivity indicator	*Demand type*	unweighted	unweighted	Residential population	Workplace population	Residential population	Workplace population	unweighted	Residential population	Workplace population
	Primary areas	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE			
Hourly pay	Car offpeak				65%					
Weekly pay	Car offpeak				68%					
	Car peak				66%					
Office rents	Bus		73%		76%		76%			
	Car offpeak			69%	77%	73%	76%		68%	70%
	Car peak				75%	69%	76%		67%	70%
	Public transport		75%	78%	80%	75%	77%		67%	68%
	Rail		75%	76%	77%	74%	75%	66%	71%	70%
Food-and-drink rents	Bus		73%	70%	83%	73%	83%			
	Car offpeak		72%	75%	78%	84%	82%		65%	65%
	Car peak		71%		76%	84%	83%			
	Public transport		73%	81%	80%	83%	81%			
	Rail	67%	73%	81%	77%	82%	78%			
Retail rents	Bus			79%	80%	81%	80%			
	Car offpeak			67%	68%	81%	76%			
	Car peak				65%	86%	78%			
	Public transport			78%	74%	79%	75%			
	Rail			76%	67%	76%	68%			

Table A9.2

A9.3.2 Normalised Accessibilities

Normalised accessibility reflects the quality of the connectivity between the origin and the available destinations. As can be seen in table A9.3, in primary urban areas there is a very strong relationship between intra-urban workplace population connectivity with rail and rent-based productivity indicators. These relationships are still significant but weaker when looking across all BUAs (rather than looking only at PUAs).

	Origin type	BUA				
	Destination type	OA11 All		OA11 Intra		
Productivity indicator	*Demand type*	Residential population	Workplace population	Residential population	Workplace population	
	Primary areas	TRUE	TRUE	TRUE	TRUE	ALL
Office rents	Rail		69%			
Food-and-drink rent	Rail				75%	67%
Retail rent	Rail	71%		76%	80%	68%

Table A9.3

Moreover, there are also relatively strong relationships between total normalised accessibilities by rail and (i) office rents in the case of workplace demand, and (ii) retail rents in the case of residential demands.

A9.3.3 Flow-average speeds

Finally, in the case of Flow-average speeds, there is a strong relationship between intra-urban public transport speeds (representing how fast you can travel between connected locations from the centre of the built-up area using public transport). This relationship is particularly strong for the combination of residential demand and retail rents.

	origin_type	BUA	
	destination_type	OA11 Intra	
	demand_type	Residential population	Workplace population
Productivity indicator	*Primary areas*	TRUE	TRUE
Food-and-drink rents	Public transport	69%	66%
Retail rents	Public transport	81%	68%

Table A9.4

A9.4 Conclusion

The analysis we have undertaken suggests that there are significant relationships between some of the connectivity and productivity indicators we used for this analysis. These are particularly evident in the case of the non-normalised accessibilities and this is up to an extent expected because these represent the total amount of demand that is accessible from each activity centre. As such non-normalised accessibilities are expected to correlate with demand for activities (work, shopping, leisure) in the centre of each city and the resulting pay and rents eventually reflect the evolving supply-demand dynamics. However, the correlation results in the case of the normalised accessibility and flow-average speeds demonstrate that good coverage and higher speed of public transport connections also correlate significantly with higher earnings and rents in the centres of large urban areas in Great Britain.

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