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Estimating intra-metropolitan journey-to-work CO2 emissions: a multi-modal network approach applied to the London Region 2001

Estimating intra-metropolitan journey-to-work CO₂ emissions: a multi-modal network approach applied to the London Region 2001

Duncan A. Smith[a], Joan Serras[a].

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[a] Centre for Advanced Spatial Analysis
University College London
1st Floor, 90 Tottenham Court Road
London, United Kingdom
W1T 4TG

Tel: +44(0)20 3108 3893
duncan.a.smith@ud.ac.uk
j.serras@ucl.ac.uk

Abstract
This paper develops a methodology for estimating network distances and CO₂ emissions for UK census ward-level journey-to-work interactions. Improvements are made on existing empirical measures by providing comprehensive intra-metropolitan analysis; increasing network routing accuracy with UK public transport timetable and GPS-based average road speed data; allowing multi-modal travel; and developing metrics suitable for travel sustainability analysis. The output unit of CO₂ emissions has been selected to enable the integration of mode-choice and travel distance data, and to aid compatibility with integrated assessment applications. The methodology is applied to the case study of the London Region for the year 2001. A very high degree of intra-metropolitan variation is identified in the results. Employment sub-centres diverge in their per-capita CO₂ emissions by up to 300%, with specific problems of carbon intensive commuting to major airports and the specialised employment region of the Western Sector. These findings indicate that sub-centre travel variation may be intrinsic to polycentric urban structures. The paper discusses means to improve the methodology, in relation to issues of coefficient disaggregation and modelling more complicated multi-modal trips.

Keywords: Journey-to-work; CO₂ emissions; multi-modal; polycentric; GIS; London.

1.1 Introduction

There are several geographical research areas concerned with the efficiency of journey-to-work travel, including jobs-housing balance analysis (Cervero, 1996; Wang, 2000), excess commuting (Ma and Banister, 2007; Horner, 2004) and travel sustainability studies (Frost and Spence, 2008). Various

1

empirical indicators are used in the study of journey-to-work patterns, such as average distance travelled, vehicle miles travelled and self-containment. We argue that improving empirical indicators with more sophisticated measures of travel interactions can better inform research, and also enhance the evidence base for policy makers. Issues of intra-metropolitan analysis, handling multi-modal network travel, and providing travel sustainability metrics, are tackled here through the development of indicators of journey-to-work network distances and CO_2 emissions. These indicators are applied to the case study of the London Region based on 2001 census journey-to-work data.

The employment geography of city-regions has become increasingly complex, with multiple activity centres emerging that feature heterogeneous urban forms and transport infrastructure (Anas et al., 1998; Hall, 1999). There is a strong case for detailed intra-metropolitan travel analyses that can differentiate between sub-centres and include interactions across wider city-regions. Of the intra-metropolitan studies that do exist, there is a focus on the *a priori* definition of sub-centres to simplify travel analysis (Cervero and Wu, 1997; Wang, 2000). This approach has the problem of introducing modifiable areal unit effects, as well as overlooking travel patterns that occur outside of the defined centres. We use a different GIS technique here to model all the journey-to-work flows in a city-region at a particular zonal scale, in this case the 450,000 flows to the 3,200 UK census wards in the London study region. The extent to which sub-centres are significant is considered *after* the indicator has been calculated using mapping analysis, based on shared spatial patterns in journey-to-work behaviour.

Another challenge for indicators is the accurate modelling of multi-modal journey behaviour. Some indicators, like vehicle miles travelled, generally ignore public transport travel. Other studies do not include accurate road speeds and public transport services in their network routing. These omissions are related to underlying data sources such as national censes, which do not record detailed trip attributes such as distance travelled and information on supplementary journey stages. In this study we try to recreate probable time-minimisation journeys from census origin-destination matrices, including UK public transport timetable and GPS-based average road speed data to improve routing accuracy. We also model supplementary public transport modes, as trips in the study region often include more than one public transport mode in a single journey.

The integration of travel distance and mode-choice behaviour together using common metrics is a useful attribute for travel indicators, particularly in light of sustainability concerns. Indicators such as vehicle miles travelled and average travel distances overlook mode-choice behaviour. Previous sustainability related studies have used energy metrics as a means to combine mode-choice and travel distance patterns (Frost and Spence, 2008; Banister et al., 1997). In this study we switch to CO_2 emissions as the output unit; the rationale being to aid compatibility with integrated sustainability assessment contexts (Hall et al., 2010). Furthermore recent studies estimating CO_2 emission coefficients for the UK are available (Department for Environment Food and Rural Affairs, 2010). Facilitating integrated assessment applications is necessary for this study as journey-to-work represents only a minority of total travel- 19% of trip miles in the UK (Department for Transport, 2008). The indicators are flexible in terms of their output, illustrated in the results section, and could also be applied to other trip types where data is available.

2

The methodology developed is intended to be transferable across the UK and in other international contexts where similar data exists. Transferability is addressed firstly by using national data sources widely available to researchers, and secondly by developing the model to be implemented and run using standard desktop GIS software. GIS-based network analysis techniques are increasingly widespread in transportation research (Määttä-Juntunen et al., 2011; Mavoa et al., 2012) using tools such as ESRI ArcGIS Network Analyst, which was the software platform used for this study.

1.2 Overview

Section 2 describes the transport routing model used to derive distances travelled by particular modes from the UK census origin-destination matrices, with the road network model described in Section 2.2 and the public transport model in Section 2.3. These mode-distance results are then used to estimate CO_2 emissions for ward journey-to-work flows based on applying emission coefficients as described in Section 3. The results of the indicators applied to the London study region are then presented in Section 4, and conclusions presented in Section 5.

2. Transport Networks Routing Model

The UK census Special Workplace Statistics 2001 record origin-destination flows by workers, including the main-mode used (Office for National Statistics, 2010). The main-mode is defined as the longest distance journey stage of the trip. Essentially the model developed here uses the basic census information to try and recreate the most likely route on transport networks for each flow between ward centroids, and subsequently calculate probable mode-distances and CO_2 emissions. The model is designed as a one-way home-to-work journey in the AM Peak period (defined as 7am-9am). The routing analysis is based on minimising journey time. Whilst generalised cost minimisation would be a more accurate approach, it is not essential in this context as the key cost related decisions- the home location, workplace location, and main-mode used- are given by the census and are not predicted by the model. Generalised cost information would however help with predicting supplementary mode behaviour on multi-modal journeys, as discussed in Section 2.3.

One of the key early decisions in the model is to determine which networks to include and the degree to which these networks are integrated for multi-modal trips. The UK census main mode options are walking, cycling, car driver, car passenger, motorbike-moped, taxi, bus-coach, rail and underground-metro. Clearly the model requires a road network (for car, motorbike and taxi trips) and various public transport networks, with bus, rail and London Underground the most significant in the study area (Transport for London, 2010). Pedestrian and cycle trips are considered to be zero-emission in this study, and so these modes are not modelled as main-modes options. Pedestrian stages are however an essential component of public transport travel, and so a pedestrian network is modelled as part of public transport journeys.

Public transport trips involving combinations of rail, bus and underground are very common in the study area (see Section 2.3) and therefore the public transport networks are modelled in an integrated fashion to enable these interchanges. Additionally there are further types of multi-modal trip that the transport model is unable to handle. Trips involving driving to rail stations are relatively

frequent, especially for residents in the wider metropolitan region travelling to Central London. Such trips are more complicated to model as they require distinct access and egress legs, as discussed in Section 2.3.

Another challenging issue for the model is the temporal discrepancy between datasets. The journey-to-work data is from 2001, and an update of this data will come from the 2011 census, available around 2013. The problem is that much of the transport network data, such as the public transport timetables, has only been made available recently from 2007 onwards. The consequences of this data discrepancy are that some public transport travel times will be under-estimated for 2001, due to improvements in the public transport network, and road average speeds will have changed. These discrepancies will decrease the accuracy of journey time predictions. On the other hand, their impacts on journey distance predictions– the key model output for this research– will be more marginal.

2.1 The Study Area

The London Region has been chosen as the study area due to its relatively large scale and extensive multi-modal transport networks. These features suit the development of composite indicators such as CO_2 emissions to help summarise complicated journey-to-work patterns. London comprises an urban core, defined here by the Greater London Authority boundary, with 7.75 million residents (Greater London Authority, 2011), and a wider metropolitan region connected to the core (Hall and Pain, 2006). In 2001, around 850,000 commuters crossed the GLA boundary on a typical working day (see Table 1), thus emphasising the necessity of a regional approach. In this research we define the metropolitan region according to a 10% commuting threshold into the GLA core area, as shown in Figure 1.
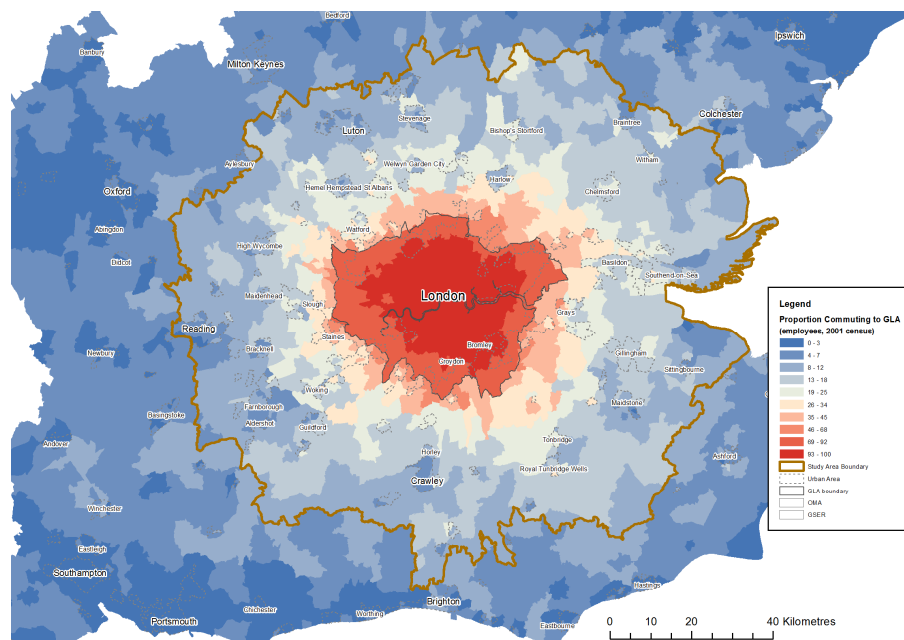

Figure 1: The Study Area Within the Greater South East, and Commuting Proportion to Greater London. Data Source: Census 2001 (Office for National Statistics, 2010).

4

Table 1: Sub-Regional Commuter Flows in the Study Area, 000's.
Data Source: Census 2001 (Office for National Statistics, 2010).

	Destination Sub-Region				
	Central London	Inner London	Outer London	Wider Study Area	Origin Sub-Region Totals
Central Ldn.	54	20	5	2	81
Inner Ldn.	345	404	103	24	876
Outer Ldn.	404	311	1,148	161	2,024
Wider Study Area	203	92	260	2,104	2,659
Greater South East	48	21	30	197	296
Destination Sub-Region Totals	1,054	848	1,546	2,487	Regional Total: 5,936

(Origin Sub-Region)

This includes towns in the immediate 50 kilometre orbit of Greater London, such as Reading and Luton, whilst excluding more distant independent cities such as Southampton and Cambridge. The wider metropolitan sub-region has a similar population and employment total to the GLA itself, dispersed across much smaller-scale settlements (Smith, 2011). To minimise edge-effects the model includes flows into the study area that begin in the Greater South East Region. Thus the transport networks are built for the entire Greater South East Region, adding nearly 300,000 external trips, as shown in Table 1. Flows that begin outside of the Greater South East are not modelled. This results in the exclusion of 107,000 trips, or 1.8% of the study area total.

2.2 Modelling the Road Network

Ordnance Survey ITN data is used to model the geometry of the road network (Ordnance Survey, 2007b). The accurate modelling of travel distances in the model depends on realistic routing analysis, ideally including the influence of congestion on route choice. Detailed average road speed information at the scale of individual links is increasingly available. Such datasets are derived from the journeys of GPS-fitted car fleets, and provide an ideal basis for realistic road network routing. The UK Department for Transport has plans to release a national dataset of average road speeds through the open data initiative. Unfortunately this output has currently been put on hold, and we look therefore to more locally specific datasets available for the London region. The specific GPS datasets used for this research are the ITIS data for the GLA area (plus M25 orbital motorway) supplied by Transport for London (ITIS Holdings, 2007), and E-Courier data for the wider South-East region (Ecourier, 2007).

The ITIS average road speed data has been validated against other independent TfL average road speed datasets within the GLA area and found to be accurate (Transport for London, 2005). There are over 1.28 million link observations for the AM peak period, providing a comprehensive dataset of average road speeds. Unfortunately an equivalently rich dataset was not available for the metropolitan region beyond the M25 in this research. For the wider region an alternative E-Courier 2008 dataset was used. The company E-Courier perform delivery services in the South East region and have released their fleet GPS data open source (Ecourier, 2007). The E-Courier data was firstly

calibrated against the more robust ITIS data within the M25 area, and then used to estimate speeds on the major roads beyond the M25.

GPS-based average speed datasets rarely cover every single link, as the number of observations on minor roads can fall below minimum sample thresholds. Therefore a method was required to estimate average speeds for those roads that lacked sufficient GPS observations. A simple approach was taken of dividing roads by their classification (motorways, a-roads dual carriage, a-roads single carriage, b-roads, minor roads, local streets) and assigning roads with the average speed for their road class within their spatial sub-region. The sub-regions were defined as Central London, Inner London, Outer London and the Wider Metropolitan Region, reflecting the macro-relationship of congestion being concentrated within Central London and tailing off with distance from the centre. Within the M25 the ITIS data covers the entire strategic road network and so the missing values are restricted to local and minor roads. The missing road links generally occurred in the wider metropolitan area due to the sparser nature of the E-Courier data. Congestion is much lower outside of the M25 and so the impact of the missing E-Courier data is less acute.

The results of the average road speed model are shown in Figure 2, with line thickness representing average speed. The severity of congestion within Central London is clearly shown, as is the lack of road accessibility in South London. The considerably greater speeds on the motorway and a-road networks are highlighted, and this will influence route choice decisions towards less direct journeys using major roads, such as the M25 orbital motorway. Based on this model we can estimate road distances for minimum travel time trips between census ward centroids. There are several uncertainties in this calculation, such as parking delays, and junction delays. These issues limit the use of the model for the precise calculation of journey time, although they have minimal impact on journey-distance accuracy.
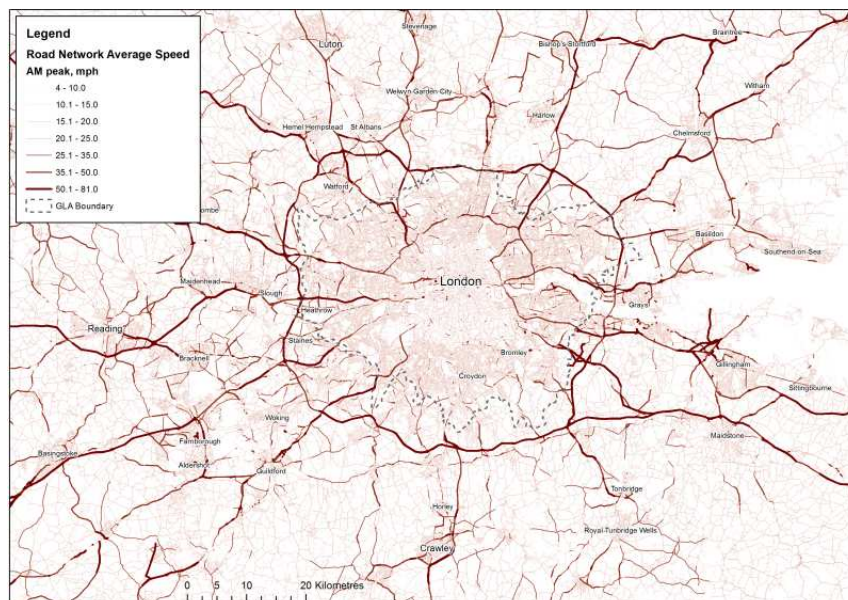

Figure 2: Greater London Average Road Speeds, AM Peak. Data Sources: (Ordnance Survey, 2007b; ITIS Holdings, 2007; Ecourier, 2007).

2.3 Modelling Public Transport Networks

The public transport model is developed as an integrated network of the rail, bus and underground modes, connected by the pedestrian street network. The pedestrian network uses the same ITN data as the road network with motorways removed and walking speed set at 5 km/h. The interchange nodes for entry and exit from public transport networks are supplied by the NAPTAN dataset from the DfT (Department for Transport, 2010a), which has the key feature of sharing reference codes with the public transport timetable data format TransXchange (Department for Transport, 2010b). There are a number of stages in developing the public transport model discussed below. These are deriving a service network from the timetable data; calculating distances for the service network; developing an interchange algorithm within GIS; and finally building a rule set for multi-modal trips.
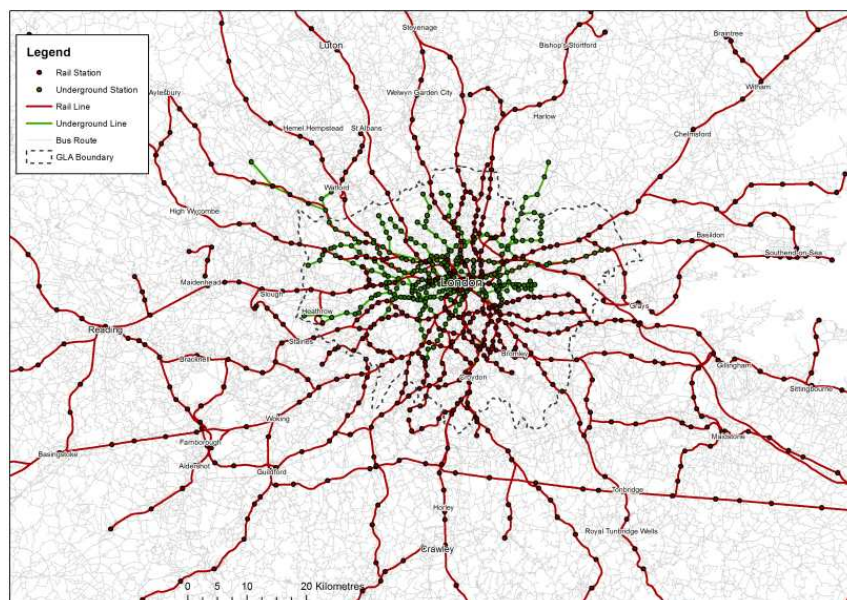
The development of a UK-wide public transport journey-planner website in the early 2000's led to the publishing of timetable data in a standard XML format known as TransXchange (National Public Transport Data Repository, 2010). The TransXchange data is highly comprehensive and voluminous, and needs to be simplified to be used for this research application. The approach taken is a service-based approach, with each public transport service (e.g. London number 7 bus, Peterborough to Kings Cross train, Victoria Line underground service) given a separate link geometry with attributes relating to service frequency, distance and time. The frequency and time attributes are averaged across the AM peak period of 7am to 9am. The advantage of the service based approach is that it allows features like express services, which do not stop at all stations, to be accurately modelled.

For the multi-modal routing to be realistic we require the model to estimate delay times resulting from interchanges. The wait time is calculated as half the service headway on the bus and underground networks. Behaviour on the mainline rail network is somewhat different as the more reliable services will reduce average wait times. Therefore wait time is calculated as a third of service headway on main-line rail. Within the GIS framework, the model is required to differentiate between types of interchanges and their related delays. This is achieved by giving all links a Service ID, and implementing the basic algorithm shown in Figure 3. With this algorithm wait times are incurred only when the Service ID changes, i.e. when there is a change in the public transport service. Wait times on the pedestrian network are set to zero, thus no delays are incurred when alighting from public transport services. In addition to wait times, another type of interchange delay relates to accessing public transport platforms. Modelling specific delays for the hundreds of stations in the study region was beyond the scope of this research, and instead standard delays for different types of interchange were applied, ranging between three minutes to travel from a mainline rail platform to the street network, to five minutes to travel from an underground platform to the street network.

An issue with the timetable service-based approach is that it produces straight-line links between interchange points. Ideally network distances should be used for the emissions calculation. To calculate network distances between stations, infrastructure networks for rail and underground networks were built using Ordnance Survey Meridian (Ordnance Survey, 2007a) data as shown in Figure 4, and distances were calculated as shortest paths between the NAPTAN nodes. A similar approach for calculating distances on the bus network was carried out using the road network as the infrastructure network. In this way, mode-specific infrastructure distances are calculated and then set as attributes for each service link. The network distances are accumulated by the model during the network analysis routing phase.

Figure 3: Public Transport Interchange Time Algorithm
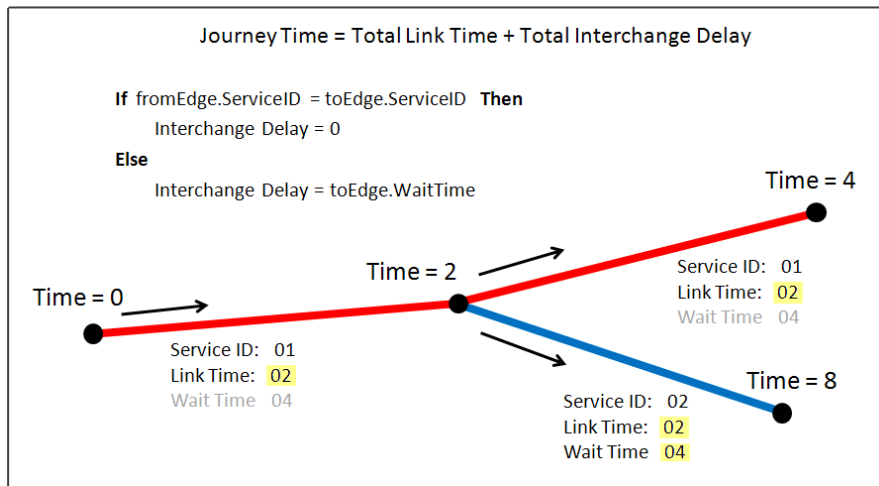
The last stage in the public transport modelling is to determine the method for considering multi-modal trips. The number of potential multi-modal combinations is very high, and we need an approach to reduce these options into the most probable combinations. A hierarchy rule is used for public transport trips, whereby the faster longer-distance public transport modes are allowed to interchange with slower more local modes, but not vice-versa. Main-line rail trips are allowed to interchange with the underground and bus networks; underground can interchange with the bus network; and bus network trips cannot interchange with the higher modes. Evidence from the National Travel Survey shown in Table 2 indicates this basic hierarchy rule largely fits with typical journey behaviour for multi-modal public transport trips.

Figure 4: Public Transport Networks. Data Sources: NAPTAN (Department for Transport, 2010a), Ordnance Survey Meridian (Ordnance Survey, 2007a).

The main problem for the public transport model is its inability to handle interchanges between car and public transport travel. Evidence from the National Travel Survey indicates that around 30% of public transport journey-to-work travel in the study area involves an initial car stage (Department for Transport, 2001). Such trips are connected to rural residents accessing rail stations, and to the advantages of the car for facilitating trip chaining (e.g. school run and journey to work). Modelling

this travel behaviour would require a more sophisticated model that could split journeys into the main stage, plus access and egress stages each of which have distinct mode options. These access and egress stages would ideally be analysed using a generalised cost modal-split modal to estimate likely proportions of potential modes. This analysis cannot be satisfactorily included in the current modelling framework. Subsequently these journeys are modelled as public transport travel only. This approach will lead to a moderate underestimation of CO_2 emissions for these trips.

Table 2: Multi-Modal Public Transport Journey-to-Work to/from Greater London[a] 2001.
Data Source: National Travel Survey (Department for Transport, 2001).

Main Mode	Proportion of All Commuting Trips	Multi-Modal[b] Public Transport Trips	Train Interchange	Underground Interchange	Bus Interchange
Train	20.0%	49%	100%	34.8%	20.5%.
Underground	12.3%	25.6%	5.5%.	100%	22.0%
Bus	11.3%	4.1%	0.8%.	3.3%	100%

[a] This geographical definition is as close an approximation to the study area as is possible using the National Travel Survey. Detailed geographical disaggregation is not available.

[b] Defined as trips involving more than one public transport mode.

3. Estimating Trip CO_2 Emissions

The mode-distance outputs from the transport routing model are used to generate composite indicators of total and per-capita CO_2 emissions for each origin-destination flow. Each origin destination pair has a series of main-mode options, and mode-distances are predicted for each of these options by the network model. To translate the mode-distances to CO_2 emissions, the straightforward approach of using a fixed coefficient for each mode is used here, similar to previous studies (Banister et al., 1997, Frost and Spence, 2008). The emission factors are shown in Figure 5. DEFRA has developed a detailed methodology for producing the coefficients including profiling the UK vehicle fleet; empirical analysis of typical road conditions and driving behaviour; integrating public transport model results, and estimating emissions resulting from the production of fuels (Department for Environment Food and Rural Affairs, 2010). Other indirect emissions sources are not included, such as vehicle manufacture and maintenance.

The DEFRA coefficients cover the major transport modes available in the study area. The main challenge for this aggregate coefficient approach is the degree to which spatial and temporal patterns diverge from the average coefficient values. Several variables are London specific- the taxi, bus and underground coefficients- and thus provide a basic degree of disaggregation to the study area for these modes. However other variables are not London specific, namely the car coefficients and the national rail coefficient. London is likely to diverge from national averages in terms of occupancy and road congestion, and these factors will affect per-passenger-km emissions. On the issue of car occupancy, the UK census helpfully differentiates car drivers and car passengers, allowing separate coefficients to be estimated for these two options. The effect of road congestion

9

remains problematic. Lacking more accurate coefficients, we use the DEFRA derived car coefficients here. A more sophisticated way to tackle car emissions would be to model emissions on individual road links, leading to highly spatially disaggregate calculations. This would require the micro-calibration of emissions against the link-based GPS average speed data, and is beyond the scope of this study.
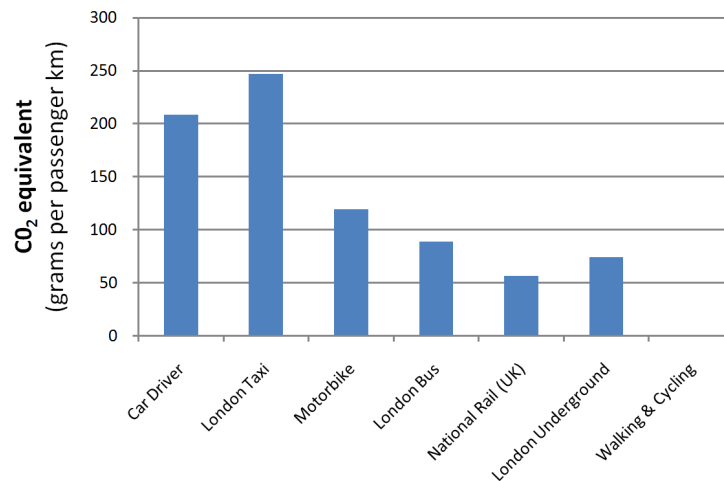

Figure 5: Estimates of Carbon Dioxide Emissions Per-Passenger-km by Private and Public Transport Modes (London values shown where available) (Department for Environment Food and Rural Affairs, 2010).

On the public transport side, emissions are also affected by similar issues of occupancy and disaggregation. Rail occupancy in London is generally higher than the UK as a whole. Again lacking more specific coefficient values, we use the national figures. Public transport is problematic in a wider sense for this methodology as emissions are less 'journey-specific' and could be considered as a product of the public transport system as a whole. The relationship between public transport supply and demand is less direct and immediate than private transport. Yet public transport is demand responsive in the longer term, and the alternative of ignoring CO_2 emissions from public transport would be misleading for policy.

Overall the choice of coefficient values has a significant bearing on the CO_2 indicator results and needs to be considered carefully. The DEFRA figures provide a useful foundation for this research, but ideally more spatially and temporally disaggregate approaches should be developed for future studies. The validation of new coefficient values is beyond the scope of this study and subsequently we have to rely on the aggregate DEFRA figures.

4. Results and Discussion

We present the CO_2 emissions indicator results for the London Region study area, and also provide a brief discussion of average distance results for additional context. The indicators can be presented in several forms including as totals and as per-capita results, and can be mapped either by residential origins, workplace destinations or a combination of both. Applications of these various outputs are discussed.

4.1 Journey-to-Work Distance Analysis

Average trip distances are a measure of residential and workplace integration, and are useful for jobs-housing balance and labour market analysis. Per-capita network distances for all trips are mapped by residence in Figure 6 and by workplace in Figure 7. A high degree of intra-metropolitan heterogeneity is evident, ranging from 3km to 30km, supporting the intra-metropolitan approach of this research. By residence the pattern follows general accessibility theory, with longer distance travel from isolated rural areas and shorter distances for residents in larger urban centres (Banister, 1997). Additionally longer residential travel distances are found to the eastern part of the metropolitan region, linked to weaker local employment opportunities in this sub-region (Smith, 2011).
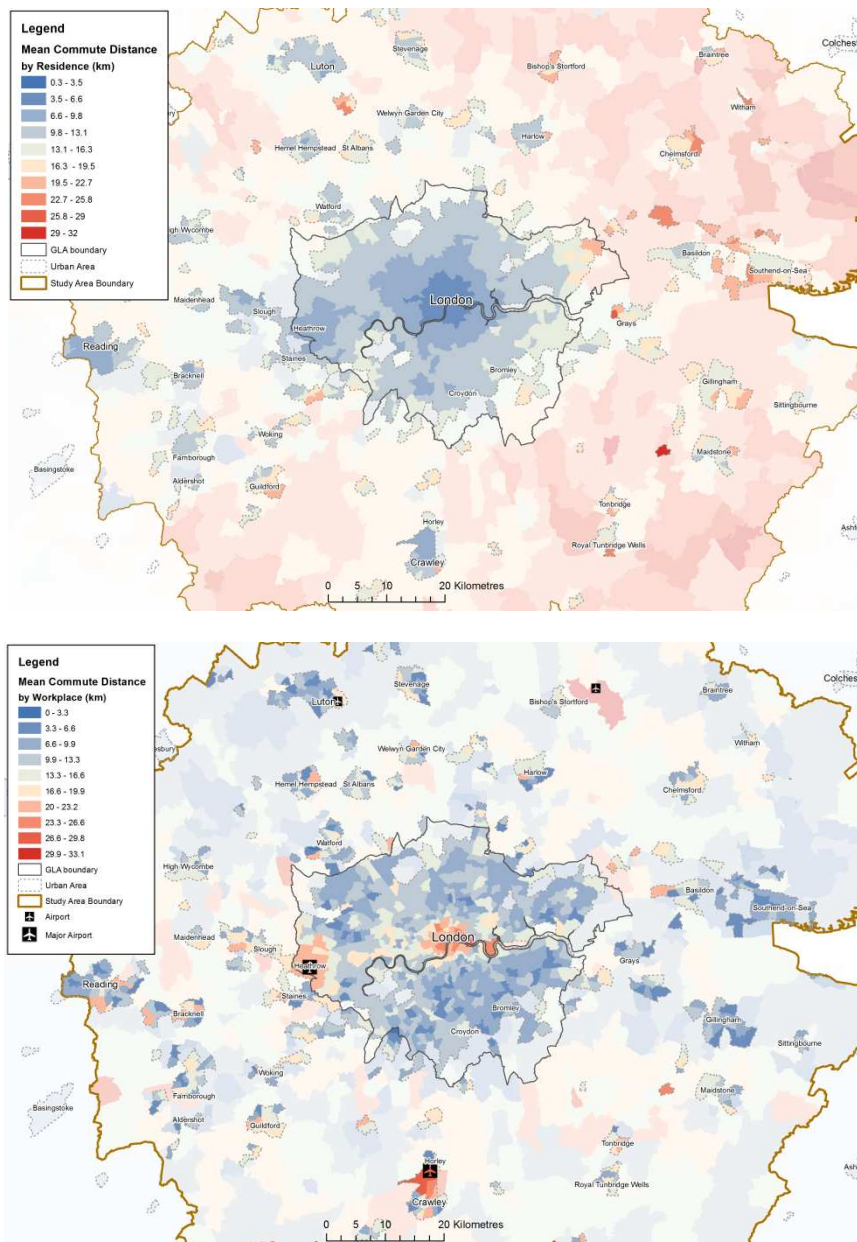
Figures 6 & 7: Mean Journey-to-Work Network Distance by Residential Trip Origin (above) and Employment Trip Destination (below). Data Source: Census 2001 (Office for National Statistics, 2010).

By workplace the results are dramatically different, with longer trips corresponding to specific centres, particularly Central London, major airports and several centres in the wider region, particularly to the west. The reasons for the contrasting workplace distribution are more complex and are the subject of further research. Long distance travel to major business centres such as Central London is likely connected to specialised high-income labour markets, and the expensive and restricted housing opportunities in these areas (Smith, 2011). Airports, on the other hand, are generally lower skill and wage level employment centres. In the London Region they present extreme examples of jobs-housing imbalance, with very large and expanding employment concentrations in isolated suburban and rural areas.

4.2 CO_2 Emissions Indicator Analysis

The CO_2 emissions results can be presented as total emission measures or as per-capita measures, with each providing complementary insights into journey-to-work patterns. Table 3 provides a matrix of total emissions according to origin and destination sub-region. This illustrates how higher emissions are concentrated in certain types of flow. The destination totals at the bottom of Table 3 show that jobs in Central and Inner London together account for 25% of emissions, Outer London jobs account for another 24% of emissions, with the remaining 51% of emissions resulting from trips to jobs in the Wider Study Area. Thus half of all emissions are from employees outside of Greater London, strongly emphasising the necessity of a regional perspective. The highest emission trip types generally involve interactions across the GLA boundary, particularly trips from the Wider Study Area to Outer London (10.3% of total emissions) or the reverse commuting case from Outer London to the Wider Study Area (7.5% of total emissions). These findings generally correspond with Frost and Spence's (2008) energy based analysis.

Table 3: Total Journey-to-Work CO_2 Emissions by Origin and Destination Sub-Region
(units: 000's $kgCO_2$; one-way AM peak trip only)

| | | Destination Sub-Region (Units 000's $kgCO_2$) | | | | | | | | | |
| | | Central London | | Inner London | | Outer London | | Wider Study Area | | Origin Sub-Region Totals | |
		Total	%	Total	%	Total	%	Total	%	Total	%
	Central Ldn.	8.7	0.1	10.3	0.1	8.9	0.1	9.8	0.1	37.9	0.3
	Inner Ldn.	212.8	1.6	195.4	1.5	173	1.3	147.8	1.1	729	5.5
Origin Sub-Region	Outer Ldn.	557.2	4.2	530.5	4.0	1,137	8.6	780.5	5.9	3,005.2	22.6
	Wider Study Area	724.1	5.5	491.1	3.7	1,374.4	10.3	4,012.6	30.2	6,602.3	49.7
	Greater South East	373.3	2.8	229.2	1.7	511.2	3.9	1,799.2	13.5	2,913.1	21.9
	Destination Sub-Region Totals	1,876.2	14.1	1,456.6	10.1	3,204.7	24.1	6,749.9	50.8	Regional Total: 13,288 $MgCO_2$	

Mapping techniques can be used to investigate the more detailed intra-metropolitan geography of the CO_2 indicator results. In Figures 8-10 the residential and workplace results are combined in the same map, using a combined total in Figure 8 and weighted averages according to the proportion of residents to workers in Figures 9 & 10. This approach reduces the number of figures required whilst

retaining the main spatial patterns. The *total* emissions results are mapped in Figure 8, highlighting the highest employment density areas of Central London and the large airports. A per-capita analysis is necessary to provide context for the total emission results, as shown in Figure 9. There are several similarities between Figure 9 and the distance maps in Section 5.1. High per-capita emissions are found in rural areas and to the west of the wider region in the economically significant area known as the Western Sector (Smith, 2011). Extremely high per-capita emissions result from commutes to airports. An important difference between the distance results and the per-capita CO_2 emission results is the relatively low CO_2 emissions for Central London. This reflects how long distance travel is offset by high levels of public transport use, and emphasises how both distance and mode-choice data is needed for travel sustainability assessments.
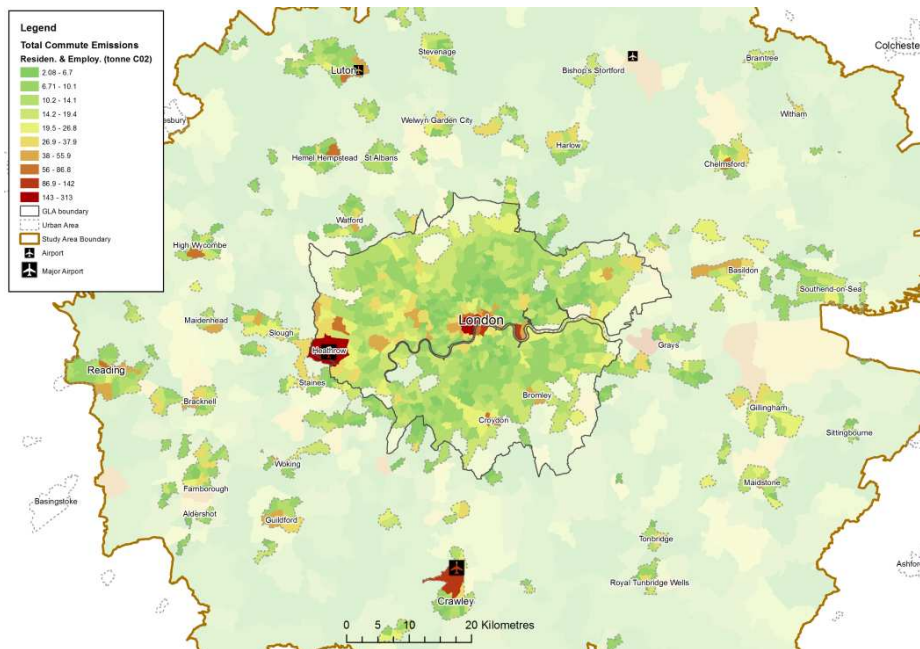

Figure 8: Total Journey-to-Work CO_2 Emissions, Combined Residents & Employees, 2001.
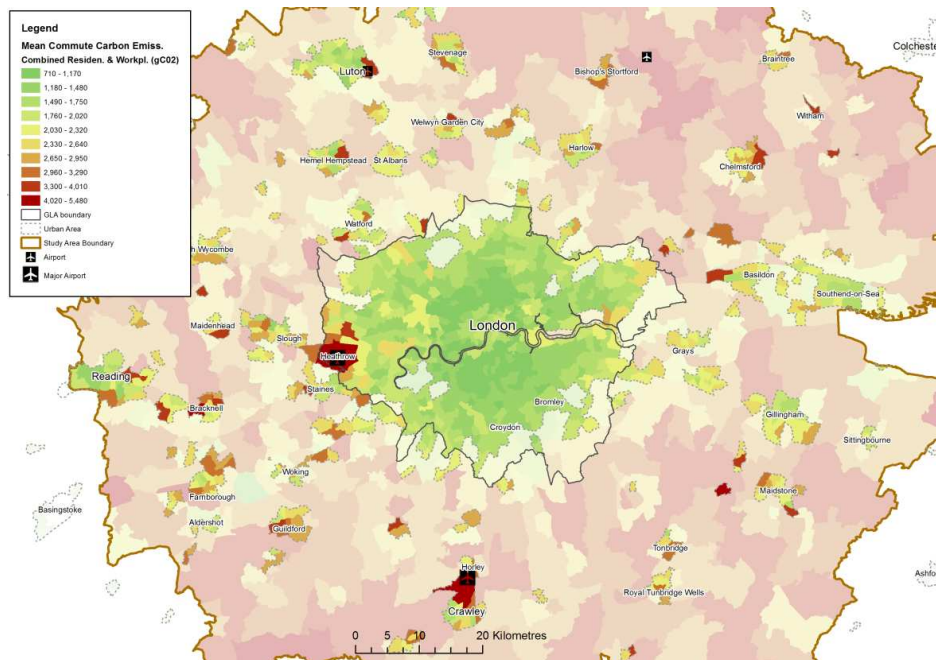

Figure 9: Per-Capita Journey-to-Work CO_2 Emissions by Combined Residents & Employees 2001.

13

The per-capita analysis in Figure 9 displays clear travel sustainability advantages for residents and employees located in Greater London compared to the wider region. It could be argued however that such differences are inevitable given the contrasting geographies of the urban core and rural hinterland. We can also focus the analysis specifically on Greater London, as shown in Figure 10, revealing a further level of variation. Note that the map classification ranges have been adjusted in Figure 10 to fit the lower emission distribution within the GLA area. Generally Outer London has higher emissions than Inner London, and the Central Activities Zone has moderately higher emissions compared to the surrounding Inner City ring, due to the longer distance travel and the lower proportion of residents. Patterns specific to individual employment centres are discussed in Smith (2011). Overall the results indicate that heterogeneity exists across several scales of analysis, with more subtle variation for centres within Greater London in addition to the wider regional pattern favouring large urban centres compared to isolated towns and rural areas.
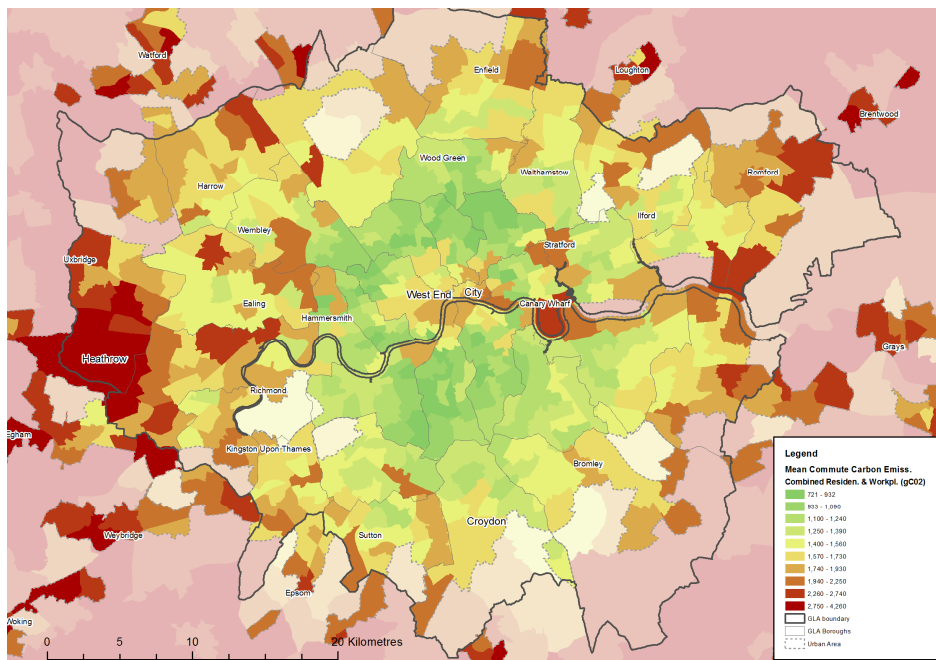

Figure 10: Greater London Mean Journey-to-Work CO_2 Emissions, Combined Residents and Employees 2001.

4.3 Conclusions and Further Research

This research has developed indicators of intra-metropolitan journey-to-work distances and CO_2 emissions for the London Region, incorporating network routing and multi-modal trips to improve indicator accuracy. The CO_2 emissions approach is useful for combining distance and mode-choice patterns into a single composite indicator. The results identify a high degree of intra-metropolitan variation in per-capita CO_2 emissions in the study area, both across the metropolitan region and within Greater London itself, with employment centre CO_2 emissions diverging by up to 300%. Thus we can conclude that the travel sustainability performance of sub-centres in the London Region is highly variable and furthermore, in light of wider research evidence (Cervero and Wu, 1997; Wang, 2000; Aguilera, 2005), it is probable that sub-centre heterogeneity in travel patterns is intrinsic to

contemporary polycentric urban regions more generally. Geographically disaggregate urban sustainability indicators are needed to understand this heterogeneity.

The results of the CO_2 emissions indicator highlight in which locations distance and mode-choice patterns offset each other in travel sustainability terms, and alternatively where these factors reinforce each other to produce the highest or lowest emissions in the study area. In Central London the long distance travel patterns are offset by public transport dominance, consequently resulting in moderately low per-capita emissions. In the remainder of Inner London, public transport and non-motorised trips are combined with much shorter distance travel, and consequently the lowest per-capita emissions in the study area are found here. Meanwhile at airports and several other business park locations, long distance travel is combined with car dominated trips to produce the highest per-capita CO_2 emissions.

A number of methodological challenges were identified in the calculation of the indicators. These relate to building the transport networks, handling multi-modal trips and estimating CO_2 coefficients. There are several areas that could be improved on in future studies. The coefficient values are a particularly important issue as they determine the weightings applied to the different modes and strongly influence the results (Frost and Spence, 2008). Essentially the greater the degree of spatial and temporal disaggregation in the coefficient values used, the more accurate the emission estimation. The use of national average values in this research is problematic. For car trips, modelling emissions on a link-by-link basis would be a significant improvement, and would complement the network analysis approach of this research. This advance would require the calibration of typical emissions against the GPS average speed and road classification data. Information on public transport occupancy specific to the study area would also improve accuracy. Generally the use of national coefficient figures in this paper will likely have the effect of underestimating car emissions and overestimating public transport emissions.

Some progress has been made in this research on the issues of network routing and multi-modal trips. The model is able to handle multi-modal public transport trips in a realistic manner, which is useful for large cities such as London where public transport modes are highly integrated. The model does not include car-public transport trips, which is problematic given that these occur relatively frequently in the study area. This will lead to moderate underestimation of emissions from public transport journeys, particularly rail journeys. The derivation of journey-to-work time would be a useful improvement to the model, and would require the validation of the model against geographically specific travel diary data.

Finally an important addition to the research would be to augment the 2001 analysis with the consideration of change over time. Journey-to-work data in the 1991 UK census was based on a 10% sample which prevents disaggregate analysis of the type pursued here. A future update with 2011 census data would allow temporal trends to be considered and identify how the performance of particular centres is changing over time. More dynamic issues such as relationships between rapid growth centres and changing journey-to-work patterns could be explored.

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16

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