

**Urban scale modelling of motor traffic and cycling flow
using spatial analysis and an assessment of factors
that influence cyclist behaviour**

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ABSTRACT

To understand and facilitate modal shift to more sustainable modes of transport there is a need to model accessibility and connectivity at an urban scale using data collection and modelling procedures that require less data and specialist input than traditional transport models. This research has used spatial analysis modelling procedures based on space syntax to investigate the potential to model aggregate traffic flows at an urban scale, and to investigate the potential to apply the same methodology to model both aggregate and individual cycle flows. Cyclist behaviour has been investigated through a questionnaire to support modelling work. The research has demonstrated that spatial analysis modelling is an effective means of representing urban scale motor traffic network, however, modifications to the model were required to achieve a correlation between modelled and measured motor traffic flow comparable to other modelling procedures. Boundary weighting was found to be effective at representing traffic crossing the boundary of an isolated urban sub-area, but was not so effective at an urban scale. Road weighting was found to be effective in improving model performance by representing traffic flows along routes according to a national classification scheme. It was demonstrated that these modelling principles could be used to represent an urban bicycle network and that the impact of the modification of infrastructure on relative flows of both cyclists and motor traffic could be accommodated. The modelling approach has the potential to be extremely useful at an early planning stage to represent changes to flows across the network. A survey of behaviour identified that cyclists modify their journey to use cycling facilities such as on-road lanes and off-road paths, or to avoid particular areas perceived to be less favourable for cyclists and that analysis indicates that it is difficult to predict (25% from survey) individual route choice. Results indicate that there were more opportunities related to route characteristics that could be influenced by infrastructure changes for occasional cyclists than for frequent/everyday cyclists.

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DEDICATION

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The results generated and the interpretation contained within this thesis are those of the author and do not necessarily reflect the opinion or views of the supporting organisations.

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UNITS AND ABBREVIATIONS

ASG	Accessibility Statistics Guidance
BREEAM	Building Research Establishment Environmental Assessment Methodology
bvk	Billion Vehicle Kilometres
CIHT	Chartered Institution of Highways and Transportation
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
DCLG	Department for Communities and Local Government
DECC	Department for Energy and Climate Change
DEFRA	Department for the Environment, Food and Rural Affairs
DETR	Department for Environment, Transport and the Regions
DfT	Department for Transport
DoH	Department of Health
DTLR	Department for Transport, Local Government and Regions
dph	Dwellings per hectare
EC	European Commission
EEP	Energy and Environmental Prediction model
EU	European Union
g	Gram
GPS	Global Positioning System
GIS	Geographic Information System
HMSO	Her Majesty's Stationary Office
ICT	Independent Commission on Transport
km	Kilometre
LA21	Local Agenda 21
LSOA	Lower Layer Super Output Area
LTP	Local Transport Plan
LTS	Local Transport Strategy
MCA	Multiple Centrality Assessment
mph	Miles per hour
Mt	Million tonnes
Mtc	Million tonnes of carbon
n	Number
NICE	National Institute for Health and Clinical Excellence
NO _x	Nitrogen Oxides

NTEM	National Trip End Model
NTM	National Transport Model
ONS	Office for National Statistics
%	Percent
£	Pounds sterling
PM ₁₀	Particulate Matter up to 10 micrometers in size
PPG	Planning Policy Guidance
QVS	QuoVadis Bike
SATURN	Simulation and Assignment of Traffic to Urban Road Networks
SCOOT	Split Cycle Offset Optimisation Technique
SRCC	Spearman's Rank Correlation Coefficient
TAN	Technical Advice Note
TAG	Transport Analysis Guidance
TCPA	Town and Country Planning Association
TLRN	Transport for London Road Network
TRL	Transport Research Laboratories
UK	United Kingdom
USA	United States of America
VOCs	Volatile Organic Compounds
WAG	Welsh Assembly Government

GLOSSARY OF TERMS

Accessibility	Ease of reaching a desirable location (Hansen, 1959).
Active transport	Transport that requires physical effort to move across a space.
Axial line	A straight line of sight that combine within space syntax to form an axial map.
Connectivity	The directness of links and density of connections in a network (Victoria Transport Policy Institute, 2012).
Integration	Measure of the relationship between one axial line to all other axial lines.
Mobility	The ability to move.
Spatial analysis	Techniques that enable the investigation of the complex relationship of spaces between places.
Urban area	An urban area refer to a town or city and associated suburbs with both a dense population and infrastructure including houses, commercial buildings, roads, bridges, and railways.
Urban scale	Urban scale considers the interaction of built environment components of urban areas as a whole.

THESIS OUTPUTS

Journal Papers

Jones, P.J., Patterson, J.L., Lannon, S.C., 2007. Modelling the built environment at an urban scale - Energy and health impacts in relation to housing. *Landscape and Urban Planning* 83 (1), pp. 39-49.

Patterson, J.L., 2004. Evaluating the success of cycle networks and predicting future use. *Traffic Engineering and Control – The International Journal of Traffic Management and Transportation Planning*. 45 (1) pp. 17-20.

Jones, P.J., Williams, J.L., Lannon, S.C., 2000. Planning for a sustainable city: An energy and environmental prediction model. *Journal of Environmental Planning and Management* 43 (6) pp. 855-872.

Conference Papers & Presentations

Patterson J.L., Jones, P.J., Lannon, S.C., Weaver, N. 2003. Modelling the built environment to assist with planning for sustainable development. *Sustainable Urban Infrastructure approaches solutions networking International conference*, University of Trento, Italy. COST C8 Best Practices towards Sustainable Urban Infrastructure. November 6 – 8th 2003.

Patterson, J.L., 2003. Modelling movement patterns in cities to predict the use of routes and resulting emissions. *National Society for Clean Air (NSCA) and Environmental Protection Conference*. Manchester, UK.

Industrial Journal

Patterson, J., 2004. Modelling software tracks urban traffic. *Advances Wales*.

Chapter 1: Introduction

1.1 Background

In 2007 the EU committed to move Europe to a low carbon economy and it was agreed that carbon dioxide (CO₂) emissions would be cut by at least 20% of 1990 levels by 2020 (European Commission, 2008). The UK Climate Change Act 2008 (DECC, 2008) set a target of 80% reductions on 1990 baseline UK CO₂ emissions levels by 2050. The Act set ambitious, legally binding targets, describing measures to help meet targets and enhance the UK's ability to adapt to the impact of climate change. This legislative intervention will need to be accompanied by a significant change in behaviour to achieve these targets, by reducing energy demand and through generation of energy from renewable and secure sources.

Figure 1 illustrates the trend of CO₂ and greenhouse gas emissions in the UK from 1990 to 2013. This indicates that CO₂ emissions for 2008 were only 10% lower than in 1990 with a more significant drop since 2008. Emissions of CO₂ were estimated at 464.3 million tonnes (Mt) for 2013, a 7.5% reduction from 2012, driven primarily by a reduction in the use of fossil fuel for electricity production (DECC, 2014). However, there is a significant challenge ahead to reach targets set for 2050.

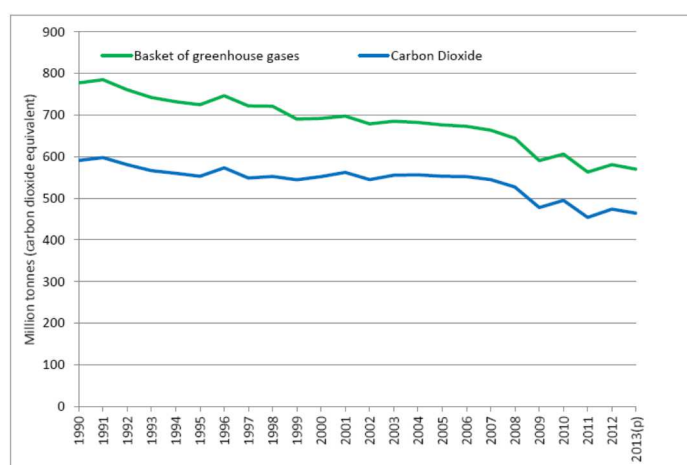


Figure 1 - Greenhouse gas and CO₂ emissions 1990 - 2013 (data for 2013(p) - predicted) (DECC, 2014)

UK transport emissions peaked at 134 Mt of CO₂ in 2007, and although this had reduced to 119 million tonnes of CO₂ by 2011, the transport sector still represents just over 25% of the total emissions of CO₂ in the UK compared to 20% in 1990 (DECC, 2014). Energy consumption by the transport sector has increased from 19% of the UK's total energy consumption in 1970 to 38% in 2011 (DECC, 2011d). Motor vehicle usage in the UK has increased more than six times from 77 billion vehicle kilometres (bvk) in 1955, to 412bvk by 1992, to 489bvk by 2011 (DfT, 2013a), a 16% increase over the last 20 years. These increases are matched across the rest of Europe, with an average of 1 car for every 2 people across the 27 member states (Figure 2).

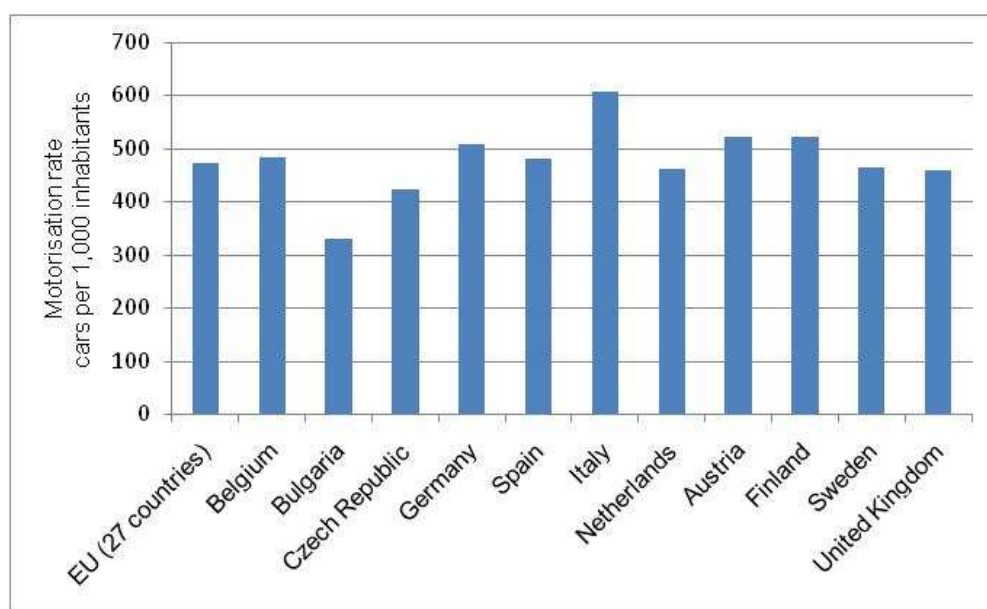


Figure 2 - Cars per 1,000 inhabitants for a sample of European countries (Eurostat, 2011)

Research at the University of Surrey (Jackson et al., 2007) has shown that energy consumption by households in the UK accounts for 165 million tonnes of carbon (Mtc) emissions per year (Figure 3), with around 50 Mtc associated with transport. Almost 20% (32Mtc) of this is attributed to recreation and leisure (which includes transport to and from recreational destinations) and 8% of emissions are attributed to transport associated with commuting.

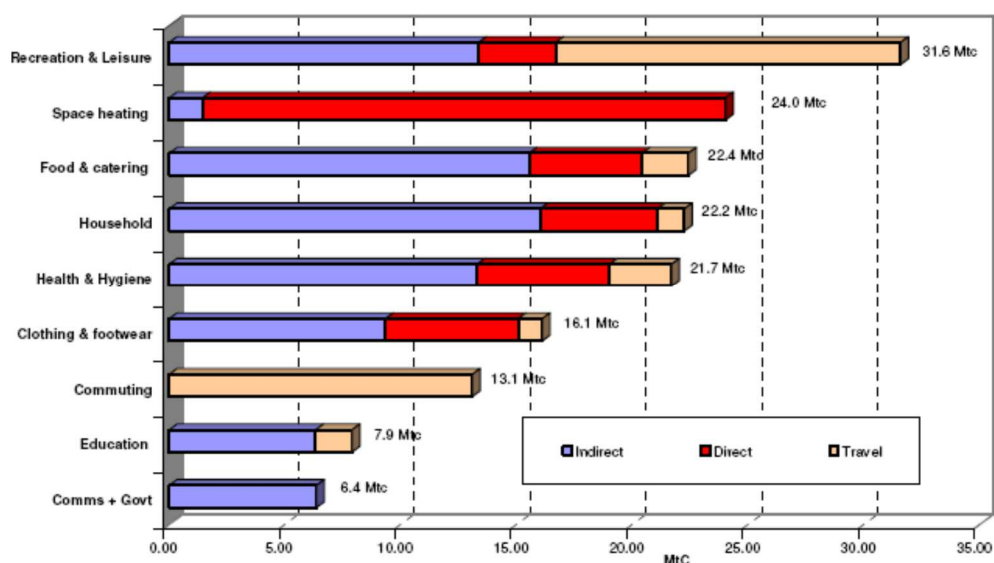


Figure 3 - Carbon allocation to consumer needs (Jackson et al., 2007) (Direct - consumption associated with fossil fuels such as cooking, heating. Indirect – upstream carbon emissions associated with the production of goods and services. Travel – emissions associated with the delivery or movement of people and commodities).

With the global population predicted to grow to over 9 billion by 2050, an increase of almost 30% compared to 2008 levels (United Nations, 2009), a significant modification of travel behaviour and fuel sources will be required, not only to reduce greenhouse gas emissions, but also to reduce reliance on increasingly scarce oil. It is estimated that world oil reserves are being depleted at an annual rate of 2.1% and that peak crude oil will be reached in 2014, beyond which time the amount of oil available for extraction will be reducing (Nashawi et al., 2010). This means that demand would be greater than supply, forcing prices up. Since the early 1990s UK transport fuel prices have increased threefold, as illustrated in Figure 4 (DECC, 2010). The amount of transport energy generated from renewable sources has increased from 0.1% of transport energy in 2004 to 3% in 2012 (DfT, 2013b).

The UK Government has limited the planned deployment of biofuels to 5% of the transport fuel market by 2013/2014 particularly as a result of uncertainties associated with land use changes, with no firm commitment beyond this point (DfT, 2013b). This is supported by a proposal by the EU to limit the use of food based biofuels to 5% as part of the Renewable Energy Directive (EC, 2012). Infrastructure changes required to utilise renewable sources to significant levels for transport will take time and financial investment to implement.

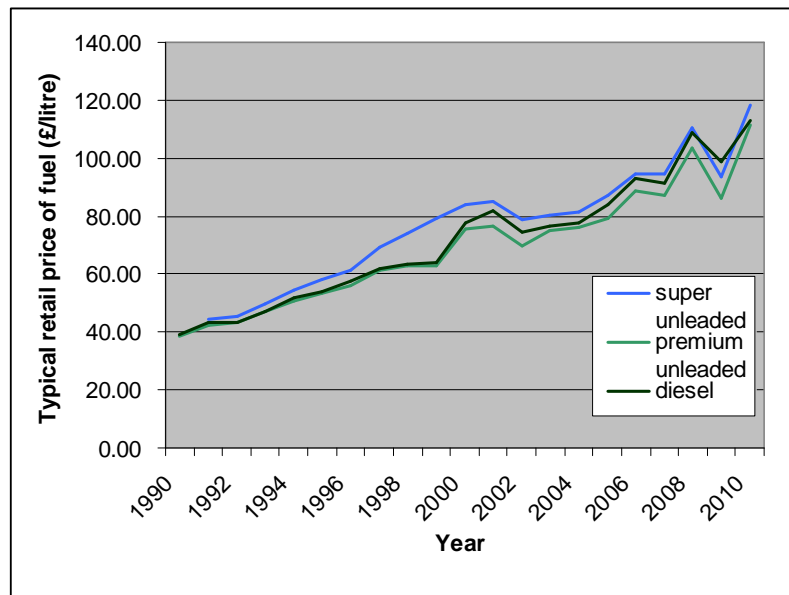


Figure 4 - Typical retail fuel prices in the UK (DECC, 2010)

People will continue to need to travel to sustain economic activity and maintain a good quality of life. However, by shifting as much of this travel, as far as is practicable, from car to more sustainable modes of transport, carbon emissions could be significantly reduced. There is therefore a need to reduce dependency on the car to achieve a low carbon future. *‘Motorised vehicles create new distances which they alone can shrink. They create them for all but they can shrink them for few’* (Illich, 1974). Over time the increased availability and use of the car has seen services and facilities become more distributed due to a reduced perceived distances. This has created the belief that a car is no longer a luxury, but a necessity to live a lifestyle that we expect and that is expected of us. A ‘proactive’ approach to achieving modal shift from

motor vehicles to other sustainable transport modes, as opposed to a 'reactive' approach (for example, due to fuel shortages) is required in order to reduce over reliance on the car.

One solution to reduce dependency on the car, particularly in urban areas, is to encourage modal shift by mobile, physically able groups of the population from car use to more sustainable modes of transport including walking and cycling for short, frequent journeys such as to work or school. By improving accessibility, defined as '*ease of reaching a desirable destination*' (Hansen, 1959) land use and activity systems within transportation networks can be better linked, therefore encouraging short journeys to be made by foot or cycle. Conventional transport planning has often focused on improving mobility (the ability to move), most often by car (Marshall and Çalışkan, 2011 and Iacono et al., 2010). However by improving connectivity and accessibility by providing a more linked transportation network, an alternative to increasing mobility is possible for sustainable modes.

Cycling is a realistic alternative mode of transport to the motor car around urban areas as it is faster than walking, assuming an average walking speed of 3 miles per hour (mph) and a cycling speed of 10-15 mph (Barton, 2010). It is potentially more favourable than the modal shift from car to public transport for shorter journeys as the user has more control over time of departure and route taken when using a bicycle and there are zero carbon emissions from the use of a bicycle. Cycling peaked in UK in 1949 when 37% of all traffic, 24 billion passenger km, was travelled by bicycle, however this had fallen to 3.7 billion passenger km (1% share) by 1973 (Golbuff and Aldred, 2011). In 2010, 817 billion passenger km per year were travelled in total, of which only 4 billion passenger km were by bicycle, just 0.5% of all travel (ONS, 2010). 16% of all journeys in the UK are commuter journeys (DfT, 2011a). The majority of this population group have the 'ability to move' by foot or on bicycle over distances of less than 5km. Figure 5 illustrates that 43% of the working population of England

and Wales travelled less than 5km to work (ONS, 2014) and as such the majority of these journeys could, in theory, make the transition from car to more sustainable modes of transport.

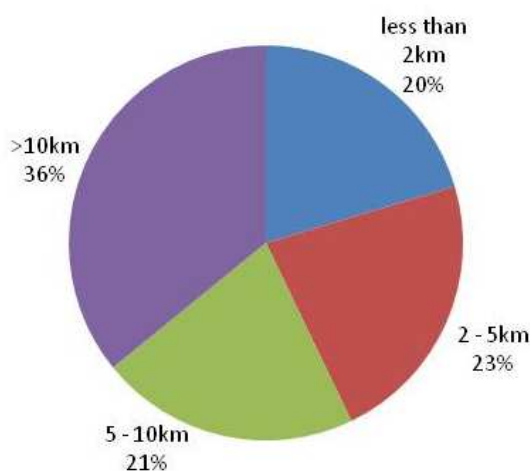


Figure 5 - Distance travelled to work in England and Wales (ONS, 2014)

Routine travel journeys, such as the journey to work and school, have been found to be repetitive, demonstrating a cyclical weekly pattern, and recognising these patterns is essential to attempt to predict future events based upon similar past events (Lapin, 1964). Wardman (2007) confirmed that commuters are also more likely to cycle where cycling levels are already high, when other things are equal. This self-reinforcing pattern may be a result of culture, image (Ortuzar et al., 2000) or due to a perceived safer environment for cyclists (Wardman, 2007).

A study by The University of Westminster (1996) demonstrated that there was little public willingness to reduce mobility in order to reduce congestion and improve the local and global environment. Transport networks should be designed to improve accessibility for more sustainable modes of transport, which have a positive impact on well-being and benefits local economies. The optimised placement of urban cycle networks to match user requirements are likely to increase modal shift which would result in carbon reductions, improvements in urban

air quality, less crowded roads, and potentially have a positive impact on health and overall quality of life.

In 1978, Hudson stated that bicycles are cheap and readily available for a large proportion of the population, they are available in a form which provides a satisfactory means of transport for work, sport and leisure and requires little change to road system for continued use. This is generally still true, however, factors such as increased motor vehicle traffic on roads and increased potential for conflict between the infrastructure requirements of cyclists and drivers, means that some modification to the road system is required to encourage and support bicycle use, alongside other modes of transport. Infrastructure to accommodate sustainable transport methods such as walking, cycling and public transport can be incorporated into built environment developments at planning and development stages of both new developments and retrofits, not only to minimise the use of individual motorised transport wherever possible, but to create safe and pleasant places to live and work whilst allowing people to move around as necessary. It is important that these developments or modifications to urban infrastructure are located in places that achieve maximum utilisation in order to justify economic investment and encourage modal shift from car to sustainable modes of transport including walking, cycling and public transport.

Investment in large scale, expensive transport infrastructure, such as city wide light rail systems is limited in the UK, particularly as a result of budget cuts due to the economic downturn of 2008. However, 'cheaper' infrastructure options combining the improvement of cycling facilities and management of motorised traffic, particularly in urban or inner city areas, can be considered as a means of achieving modal shift, which in turn will help reach tough CO₂ reduction levels set. Therefore, there is a need to combine analysis of motor traffic flow and cycling flow to investigate how changes for one mode impacts the other. By being able to

identify the most frequently used routes for both motor traffic and cyclists at an urban scale within the same process together with the pattern of utilisation, informed decisions can be made about where to modify infrastructure. By using a range of measures to channel cyclists along favourable routes, together with supporting infrastructure at the workplace, an increase of commuter cyclists might be possible.

1.2 Focus of the research

Cahill and Garrick (2008) stressed the need for planners to prioritise facilities for cyclists to present decisions made to stakeholders in a quantitative way, and for tools to evaluate these facilities. At a planning level decisions need to be made relatively quickly, simply and cost effectively using familiar techniques and modelling tools. Most existing traffic models have been developed to assist with congestion problems, to speed up traffic and to increase mobility rather than to achieve modal shift. These existing models require vast amounts of data and take a long time to establish and implement. An appropriate, validated traffic model for scoping at the initial planning stage that can be used at an urban scale and can be combined with cycle data is therefore required to assist with making quantitative assessments to help with the decision making process.

However, urban scale motor traffic flow or cycling flow should not be investigated alone as impact from one scheme may impact on another (DfT, 2014). Cycle infrastructure, in many cases, is shared with motor traffic e.g. roads, on road cycle lanes and junctions. This sharing of infrastructure leads to potential conflict and also means that promotion of one mode of transport could impact on the other. As such motor traffic modelling needs to be combined with cycling modelling, to enable the investigation of these potential impacts. Few detailed studies have estimated the demand for and benefits of new cycle facilities (Goodman,

Sahqvist and Ogilvie, 2014; Law, Sakr and Martinez, 2013; Titheridge and Hall, 2006) in contrast to the profusion of studies for motorised transport (Cahill and Garrick, 2008; Hopkinson and Wardman, 1996). Research has indicated that connectivity and directness are critical for encouraging non-motorised transport (Manum and Nordstrom, 2013; Lee and Moudon, 2006). Handy (2005) found that where cycle network accessibility had increased there was a significantly higher propensity to drive less, thus providing evidence that land planning policy can have an impact on modal shift. Routes that are considered suitable for cycling by planners, based on site visits or desk top work, may not be the routes that link origins and destinations in a way that cyclists favour.

Although engagement with stakeholders together with traditional mapping work can provide valuable data to guide planners, strategic modelling could not only assist with the development of policies intended to increase accessibility and link key origins and destinations, but also provide planners with the opportunity to identify optimal network configurations for both cyclists and motor traffic with relatively little expenditure. In the absence of a city wide, fully linked cycle network, cyclists will inevitably use the road network for part or all of their journey as this provides a facility that is generally well maintained, with a smooth surface, being well lit and overlooked. However, sharing infrastructure with little or no mitigating measures to accommodate cyclists potentially causes conflict between the two modes of transport, and could potentially discourage a greater numbers of cyclists.

Therefore to increase the number of cyclists, there is a need to improve accessibility for cyclists, and to make sure that these routes are as safe as possible for cyclists. One way to achieve this is to modify access on the road network for both cars and cyclists in such a way as to provide travel routes that meet the majority of the needs of both whilst minimising the conflict between the two modes of transport. This approach requires the need to predict where

best to improve/reduce access within cities for different modes of transport so that i) limited resources can be used more effectively and efficiently, and, ii) in order to make more informed decisions (Iacono et al., 2010) and iii) to determine the impact of these modifications on all routes to ensure that the functionality of the wider network is maintained. Understanding the movement of bicycles across a network would help in understanding the relative importance of different routes to users (Cahill and Garrick, 2008).

Urban scale planning tools are required to predict routes that will potentially be used by motor traffic and cyclists, to assist with situating cycle facilities in locations which increase connectivity and accessibility, which can map current facilities and how successful these facilities are, and which can investigate the effect of modifying road networks for both car users and cyclists. These tools need to be relatively quick and easy to use, inexpensive, fit in with current work practices and capabilities, and use computer software that is readily available and accessible.

1.3 Research aims and objectives

The *aim* of this thesis is to investigate the potential to model motor traffic and cycle flow at an urban scale using spatial analysis techniques to identify routes within a city that can be targeted to improve accessibility for cyclists.

The specific *objectives* of this research that were completed to achieve this aim are to:

- identify, test and improve a computer based spatial analysis model that can be used to quantify relative levels of motor traffic flow for an entire road system for a city or region, including both local and strategic roads, that requires as little data as possible, whilst providing meaningful and useful outputs;

- evaluate the potential for transferability of the spatial analysis modelling method tested on motor traffic for cyclist flows to identify whether the model can be implemented for cycle networks;
- identify whether there is potential for the model to illustrate the impact of changes in infrastructure on relative flow of both motor traffic and cyclists;
- identify whether the model enables choices made by individual cyclists to be predicted;
- investigate factors that influence cyclists behaviour to evaluate the use of existing cycle networks to inform the model.

The spatial analysis model will help to identify routes which are most used by motor traffic and cyclists, and assess the impact of modifications to road and cycle infrastructure. The identification of key routes would enable planners to assess how successful current urban networks are and to identify where changes to current configurations would be best located. This research contributes to the further development of space syntax as an urban scale modelling tool for both motor traffic and cycle traffic.

The approach developed could be used for scoping initial planning options or supporting planning decisions. Therefore the model should be as accurate as possible whilst being replicable, reliable and be relatively simple and quick to generate data and run. Bringing together motor traffic and cycle traffic using the same data sources and techniques could encourage cross sector working to increase modal shift.

The research focused on urban areas, where transport requirements are more concentrated and there is increased potential for modal shift due to distances travelled being generally shorter in length. Although the research was undertaken in UK cities, the findings and the methodologies developed are applicable to other international urban areas. The research does

not give guidance on the location of specific facilities as this is provided in local design principles such as those contained within the Manual for Streets 2 (Chartered Institution of Highways and Transportation, 2010) and different local authorities focus on different priorities including reducing traffic speeds, managing traffic flows and provision of on/off road routes for cyclists depending on local context. This study focused on daily household transport patterns in urban areas that are short in length and are repeated, i.e. the journey to and from work. The research assumes that investment is not available for necessary infrastructure to be installed on all roads and that funds need to be focussed in locations that will see the greatest benefit. The key is to identify routes that play an important role in the network both for motor traffic and cycling in order to assess the potential effects that infrastructure modification might have on both modes, and to allocate resources most effectively to encourage modal shift.

The research was based on data from a number of cities. Validation of the motor traffic model was undertaken in Cardiff with tests taking place on Leicester, Leeds and Neath Port Talbot, whilst cycling investigations were undertaken in Cardiff, Bristol and York. The three cities subjected to cycling investigation vary in the development of existing urban cycle networks and other factors that may influence the decision to cycle including congestion, gradient and historical development. Established relationships with local authorities in these cities also existed which enabled the provision of relevant data to develop the modelling work.

1.4 Structure of the thesis

The thesis comprises 11 chapters, these are summarised as:

Chapter 1 – Introduction

This presents the background to the research describing the requirement for the research and the aims and objectives of the thesis.

Chapter 2 – Literature review

A review of the background principles to the implementation of low carbon transport initiatives within cities including identification of policies that drive change at different spatial levels is presented together with an overview of the development and classification of urban road networks including land use patterns and infrastructures. The requirement for modal change is reviewed summarising the requirements of cyclists and characteristics of cycle routes. The use of models for traffic planning is reviewed concentrating on models that look at all roads at an urban scale with a focus on flow and accessibility of motor traffic and cyclists. The characteristics and problems of these models are reviewed.

Chapter 3 – Methodology

The methodology of the spatial modelling procedures used within the thesis is presented and the case study cities are described. An overview of the spatial analysis model is provided including a justification of why the model was selected for this research.

Chapter 4 – Validation of the spatial analysis model for aggregated motor traffic flow

The process of validation of the motor traffic flow model is described in detail including an investigation of novel methods for improving the performance of the model using different weighting factors. The procedure for applying the motor traffic flow model to other cities is described.

Chapter 5 – Results from the validation of the spatial analysis model for aggregated motor traffic flow

The results for the validation of the motor traffic flow model including quantitative and qualitative results are presented and discussed demonstrating the step by step process taken to validate the model. This includes a detailed description of the analysis of the weighting methods investigated to improve the model performance.

Chapter 6 - Demonstration of the spatial analysis model for aggregated cycle flow and motor traffic flow

The process involved in demonstrating how the spatial analysis model could be used to quantify cyclist flow rates within three cities is described together with the procedure used to investigate whether the model could quantify how changes to the transport infrastructure influences relative flows of motor traffic and cyclists.

Chapter 7 – Results from the demonstration of the spatial analysis model for aggregated cycle flow and motor traffic flow

Results from the implementation of spatial analysis of relative flow of cyclists are presented as a series of axial maps. The impact of improved accessibility for cyclists and reduced accessibility for motorists are presented as a result of changes to road infrastructure to demonstrate the potential of the model to illustrate change in flow of cycle traffic relative to motor traffic.

Chapter 8 – Collection and analysis of individual cyclist movement and behavioural data

Techniques for utilising spatial analysis to predict the route of individual journeys is presented which will help to identify whether cyclists use the most direct route available, as predicted by the model, or whether the preference is to deviate to use routes with cycling facilities or

other favourable characteristics. This is supported by the preparation and distribution of a questionnaire to investigate the influence of cyclist behaviour on route choice, the decisions behind undertaking a journey to work by bicycle, the frequency and occasions that a bicycle is used and the reasons for choosing the route taken.

Chapter 9 – Results from the collection and analysis of individual cyclist movement and behavioural data

A comparison of actual and predicted routes taken by individual cyclists is made to illustrate whether the model is capable of predicting routes taken by individual cyclists across three case study cities. Quantitative and qualitative results from a questionnaire survey to investigate the behaviour of cyclists in these three cities are presented, with the aim of identifying commonalities in behaviour across cities with regard to the extent to which journeys are undertaken by bicycle and the factors behind the choice of mode and route.

Chapter 10 – Discussion

Based on the findings of the previous chapters, the performance of the spatial analysis model for urban scale motor traffic flow is presented including an evaluation of the weighting methods applied. The potential to apply the model for cyclists at an urban scale is discussed together with combining the motor traffic and cycle traffic models. An evaluation of the potential to model individual route choices is made and this is investigated with the findings for the questionnaire survey. Benefits and shortcomings of the model are presented together with opportunities for future improvements and potential application of the model.

Chapter 11– Conclusions

Conclusions for the thesis are provided including a summary of the findings, significance and possible application and implications.

Chapter 2: Literature review

2.1 Introduction

The research, development and implementation of urban scale transport networks are affected by a wide range of physical, political and socio-economic factors. The following literature review, the structure of which is summarised in Figure 6, moves through this broad, but relevant, base before focussing on areas directly associated with the research in this thesis, namely the principles of connectivity and accessibility, and how these can be investigated using space syntax to model urban scale transport networks.

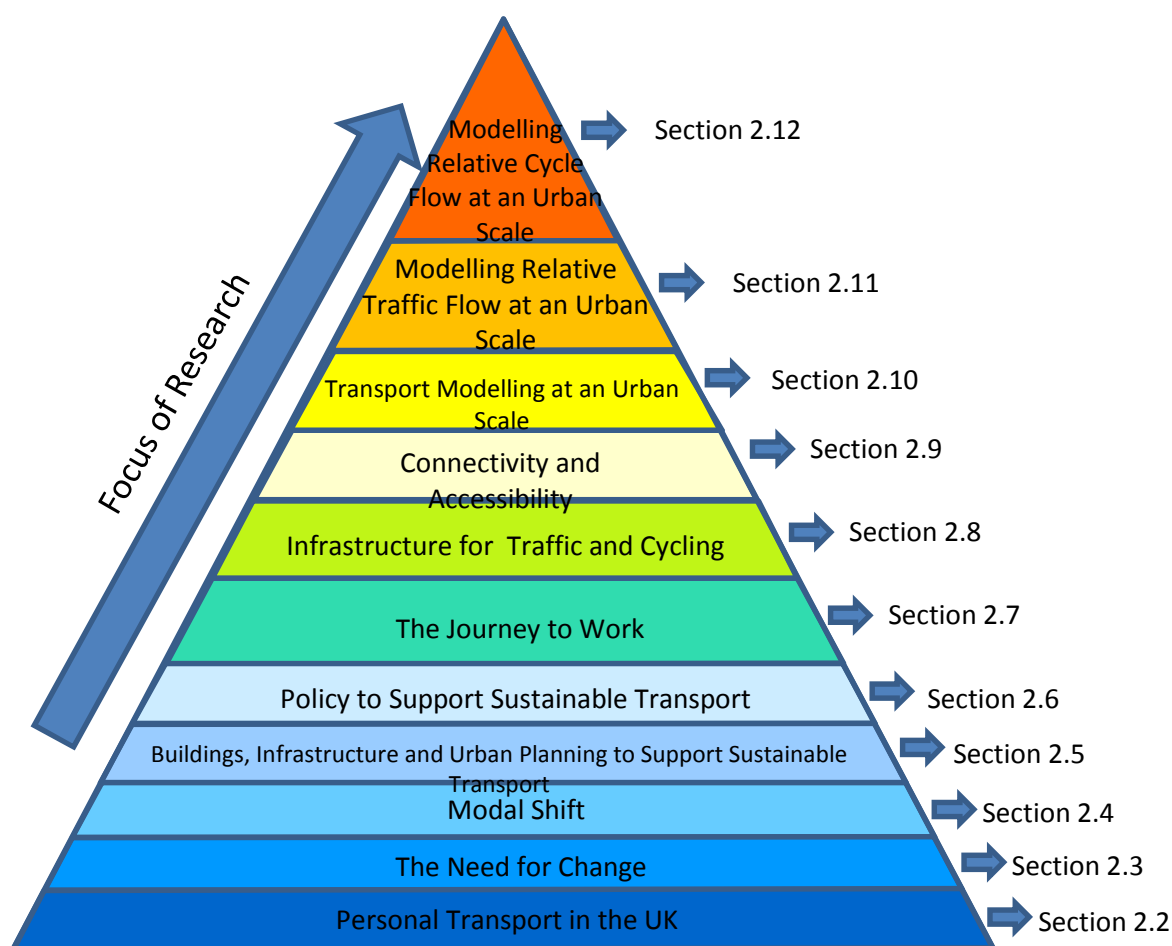


Figure 6 – Contents of Literature Review

2.2 Personal transport in the UK

The population of urban areas is increasing with 75% of the European population living in urban environments in 2010 and this is expected to rise to 80% by 2020 (European Commission, 2010). In England and Wales 84% of the population live in urban areas which accounts for only 6% of total land area (ONS, 2012). Therefore, urban areas are key to achieving global carbon reductions. An urban area can refer to a town or city and associated suburbs with both a dense population and infrastructure including houses, commercial buildings, roads, bridges, and railways.

Cities need to provide a good quality of life whilst remaining financially competitive to support residents and reduce dependency on resources, therefore creating sustainable cities. Transport is essential to achieve a successful sustainable city, *'It is a truism that transport is one of the two great 'nation building' influences (education being the other) which are basic to everything else'* (Ministry of Transport, 1963). The development of a city however needs to take account of its own strengths and weaknesses, both current and historical, in order to progress to sustainability *'As each city is different we have to find our individual ways towards sustainability'* (Aalborg Charter, 1994).

The concentrated nature of urban areas, with short distances between origin and destination, presents the opportunity for modal shift from car to a more sustainable mode to be a realistic option to reduce the negative impacts of car use, whilst maintaining positive gains through efficient mobility. Passenger cars in the UK emitted 63% of all greenhouse emissions from road transport in 2009 as illustrated in Figure 7 - . This has only slightly reduced from 66% since 1990 (DECC, 2012). On average each urban dweller makes three trips a day during the

working week and this has not changed since the 1960s demonstrating that whilst trip making propensity has not changed the means of transport has (Tolley, 1990).

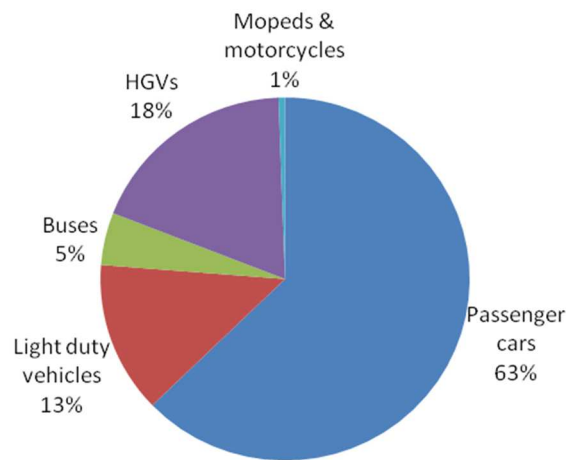


Figure 7 - Greenhouse gas emissions from road transport in the UK in 2009 (DECC, 2012)

Between 1970 and 1990 the average distance travelled by a UK resident per year increased by a third from 4,476 miles to 6,726 miles. This peaked in 1995/97 at 6,981 miles per year and has fallen slightly to 6,691 miles per year in 2012 (DfT, 2013e). Average trip length also increased by more than a third from 4.7 miles in 1970 to 7 miles in 2011 (DfT, 2013e). The number of vehicle miles travelled by cars and taxis in the UK has increased fivefold in the last 60 years, accounting for 80% of traffic on UK roads, as illustrated in Figure 8.

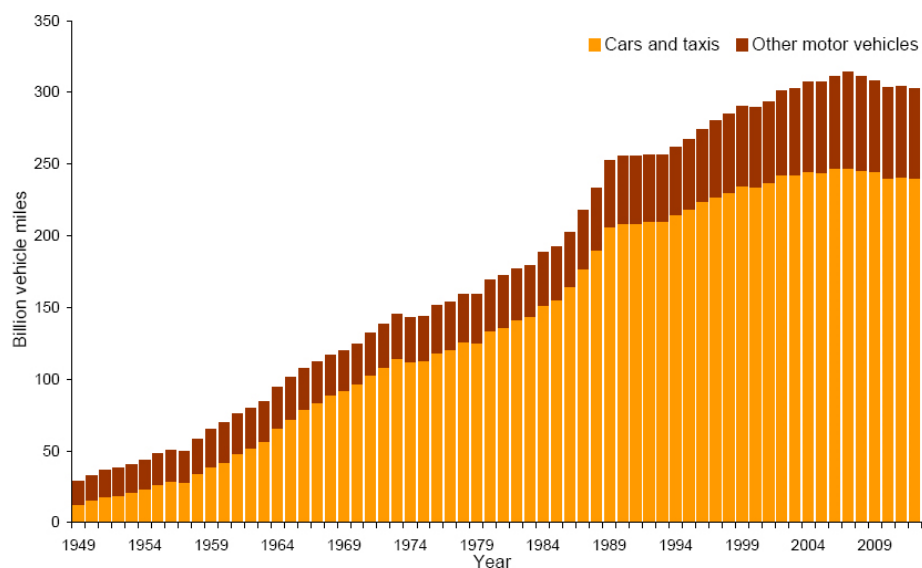


Figure 8 - Increase in motor traffic in Great Britain (DfT, 2012b)

Current data indicates that there are 34.7 million cars on the road in the UK (Energy Institute, 2013). Figure 9 presents data from the National Transport Model for the UK based on behavioural observations, traffic volumes, economics, prices and emissions (DfT, 2009b). It confirms that motor traffic is dominated by the car and that this trend will continue beyond 2035, with a rapid rise in total motor traffic, particularly cars, from 2015.

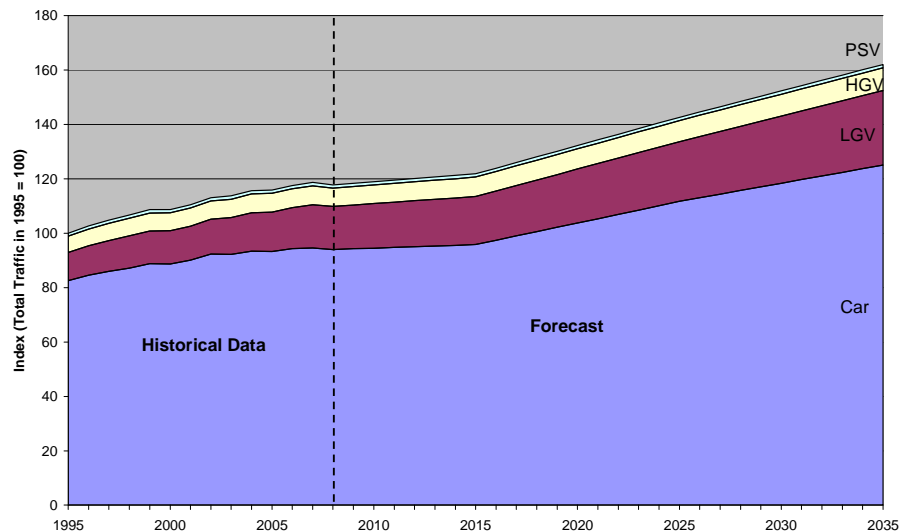


Figure 9 - Forecast growth in motor traffic by vehicle type (DfT, 2009c)

Figure 10 illustrates that the purpose of journeys in the UK is spread across business, education and leisure, with 19% of journeys made for commuting and business purposes, 20% for shopping, 30% for social visits and leisure, 20% for personal business and 11% for journeys to school (DfT, 2011a). Each journey type has different requirements, such as timing, need to carry equipment/shopping, distance to travel and complexity of journey and these influence the mode used.

Statistics describing the mode of transport employed in the UK (Figure 11) indicate that only 2% of trips were made by bicycle even though data for the previous year showed that 20% of all trips were less than one mile in length (DfT, 2009b).

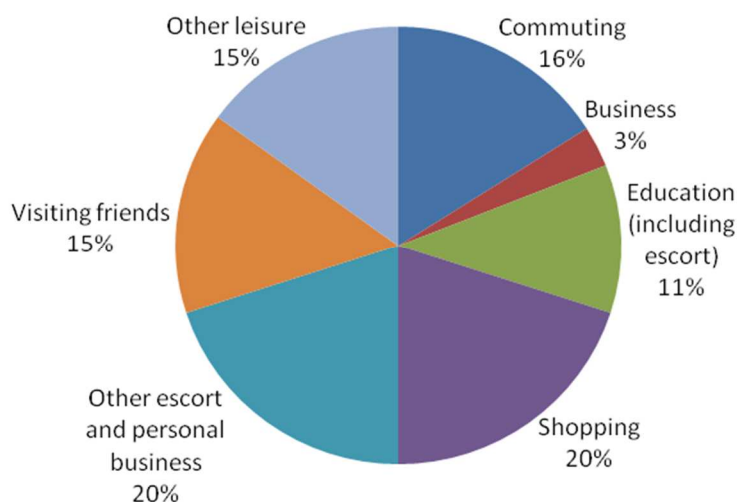


Figure 10 - Proportion of mode purpose in the UK in 2010 (DfT, 2011a)

In 2010 it is reported that the average cyclist made 6 trips a week by bicycle, travelling 16 miles which totalled a quarter of their total transport requirements (DfT, 2011a). These figures confirm the potential for modal shift.

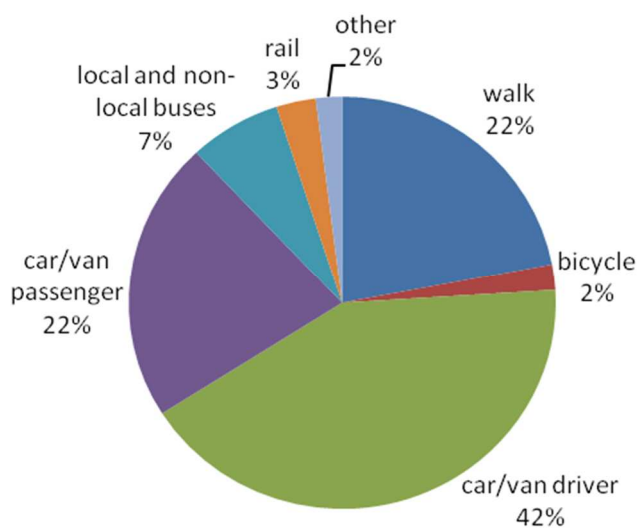


Figure 11 - Proportion of trips per mode share in the UK in 2011 (DfT, 2012a)

2.3 The need for change

Traffic is one of the main sustainability issues in urban areas, as people, and associated vehicles, move around in concentrated areas resulting in environmental, social and economic problems including:

- increased emission of air pollutants including carbon monoxide (CO), carbon dioxide (CO₂), oxides of nitrogen (NO_x), volatile organic compounds (VOCs) and particulates (PM₁₀);
- reduced visual amenity;
- reduced road safety and increased incidence of accidents;
- increased noise from motorised transport;
- congestion over longer periods resulting in unreliable journey times and delivery of goods to businesses taking longer.

Opportunities to reduce transport related CO₂ emissions can include changing fuel type, using more efficient vehicles, reducing the amount of motor traffic on the road and changing overall traffic behaviour through infrastructure and information (Tolley, 1990). The vehicle manufacturing industry is being pushed to reduce emissions through technology development. The EU New Car CO₂ Regulation (European Commission, 2009) introduced in 2009 specified that average emissions for all new cars should be 130g CO₂ per km by 2012 and that this should be reduced to 95g CO₂ per km by 2020. This is an overall reduction of 40% on 2007 levels (DECC, 2011). The introduction of more efficient fossil based transport technologies is clearly important and should be continued. However, achieving modal shift, particularly to active transport (e.g. cycling and walking), not only significantly reduces emissions, reducing dependence on fossil fuels and has a number of other societal benefits.

Research by Lovelace et al. (2011) investigated the impact of pro-cycling interventions on energy savings as a result of reduced consumption of fuel and cars and energy costs associated with the increased demand for food. A net reduction of primary energy consumption was found, with reduced fuel consumption being the largest single energy impact. This is supported by results from the European Cyclists Federation (2011) that compared CO₂ emissions produced by cycling compared to other modes. This report indicates that cycling is responsible for 21g/km, with the average car producing 271g with a bus generating 101g. However, findings by Pooley et al. (2012) have argued that the contribution that modal shift has on transport related emissions is relatively small and that gains to personal health and local environment are more significant.

Air quality in the UK has improved significantly over recent years due to reductions in emissions from individual domestic, industrial and transport sources through the introduction of cleaner technologies and fuels, as illustrated in Figure 12.

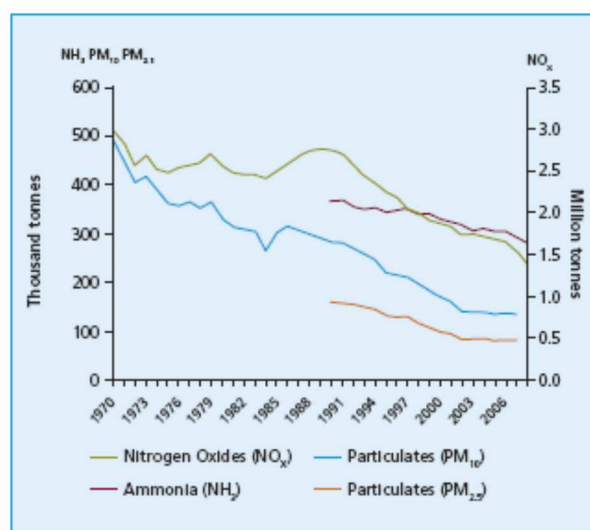


Figure 12 - Emission trends of key pollutants for the UK (DEFRA, 2010)

There has been a shift in the main source of emissions away from industry and domestic heating. Large combustion plants associated with power generation and transport are now the main two sources (DEFRA, 2010).

Health impacts associated with exposure to air pollution from motor traffic include causation or worsening of asthmatic conditions through to premature death from heart and lung disease (WHO, 2013). The World Health Organisation stated in 1946 that *‘Health is a state of complete physical, mental and social wellbeing and not merely the absence of disease or infirmity. The enjoyment of the highest attainable standard of health is one of the fundamental rights of every human being, without distinction of race, religion, political belief, or economic and social conditions’* (WHO, 1946). Successful local urban design can encourage exercise which reduces heart disease, respiratory problems, obesity, and diabetes, and improve mental wellbeing (Barton, 2010). Sallis et al. (2009) suggested that street connectivity is a major built environment feature that can have a direct impact on active transport. In 1992 the British Medical Association reported that health and the environmental benefits from cycling were more important than concerns associated with accidents (BMA, 1992). Accidents associated with road traffic reduced from 3,201 in 2005 to 1,850 in 2010 as a result of an increase in traffic calming measures, education, training and increases in speed enforcement legislation (DfT, 2011b). These figures are improving but are still significant. These, and the previously mentioned health impacts can lead to a reduced quality of life, increased costs associated with health care and reduced productivity at work and school. These impacts could be significantly reduced if levels of traffic associated with large scale modal shift are achieved.

A successful transport system is essential for a strong economy. *‘Connectivity provided by transport is crucial for a modern economy – allowing for goods to be moved to market, helping employees get to work and providing access to a wide range of services and leisure activities’*

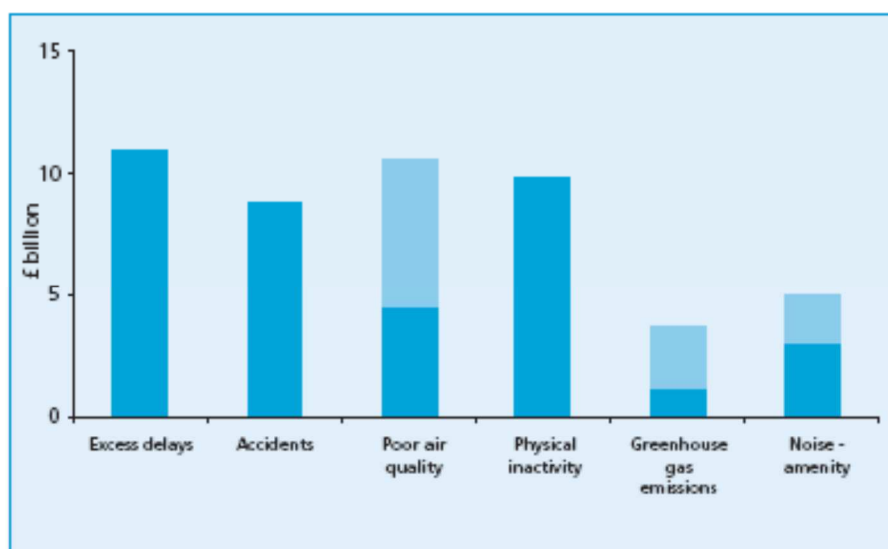
(Cabinet Office, 2009). Both direct and indirect costs are associated with the construction and operation of all modes of transport. Direct financial costs relate to building, maintenance and operation of transport equipment and are usually realised by the user of transport through purchase of equipment, taxes and general running costs. Indirect costs relate to broader impacts associated with the means of transport, infrastructure and its operation and are much more difficult to assess. The true cost of a journey by car should include personal direct costs such as fuel, parking and general running costs together with broader costs including congestion, noise, accidents, pollution and impacts on accessibility.

A study looking at the indirect costs of transport in urban areas in England, including congestion, poor air quality, accidents and physical inactivity identified a combined cost of around £10 billion per year on the UK economy (Cabinet Office, The Strategy Unit, 2009).

This indicates that, as illustrated in

Figure 13, higher financial costs associated with excess delays are predicted, together with increased financial burden on health care relating to accidents and physical inactivity and poor air quality are potentially equally significant.

Costs relating to greenhouse gases are reportedly much lower, but the impact of climate change is much more difficult to assess, particularly on a global scale over long timescales, and it is likely that this is significantly undervalued. This indicates the potential of improving the effectiveness of the road network and including facilities for sustainable transport options in urban areas, financial cost savings can be made alongside the non-financial benefits.



Note: Units are £ billion per annum

Paler areas represent uncertainty associated with air quality, greenhouse gas emissions and noise

Figure 13 - Comparison of the wider cost of transport in urban areas in England (Cabinet Office, The Strategy Unit, 2009)

2.4 Modal shift from car to bicycle

To reduce the direct and indirect costs associated with motor traffic, urban dwellers need to change their behaviour to more sustainable modes of transport. There is a need to demonstrate that there are real alternatives available for certain trips, whilst acknowledging that not all modes are suitable or convenient for all journeys. The most reported factors that prevent people from cycling are journey distance, gradient, traffic safety, heavy motorised traffic, inconsiderate drivers, pollution, bad weather, fitness and social pressure (Gaterslaben and Appleton, 2007). Huwer (2000) indicated that many factors influence national and regional variations in cycling uptake including availability and price of bikes, degree of motorisation, density and concentration of land use, gradient, as well as income, social attitudes and weather. These factors, where possible, need to be removed or improved in order to see a significant increase in the number of cyclists.

Several countries in mainland Europe have been successful in encouraging cycling as a realistic and effective alternative to the car for short journeys. In countries with high levels of cycling, including the Netherlands, Denmark and Germany, the public are more committed to protecting the environment, green parties have a greater role in Government and there is a willingness by individuals to change travel behaviour (McClintock, 2002). In The Netherlands, 27% trips are made by bicycle which, as illustrated in Figure 14 – Overview of cycling in a selection of European countries (Pucher and Buehler, 2008)Figure 14, contrasting with levels well below 5% in the UK, Italy and France (Pucher and Buehler, 2008).

Country	Share of cycle trips (%)	Cycle distance per person per day (km; 2000)
UK	1% (2005)	0.2
Ireland	2% (2002)	0.5
Italy	2% (2000)	0.4
France	3% (1994)	0.2
Norway	4% (2001)	-
Austria	5% (1995)	0.4
Switzerland	6% (2000)	-
Belgium	8% (1999)	0.9
Germany	10% (2002)	0.9
Sweden	10% (2000)	0.7
Finland	11% (1998)	0.7
Denmark	18% (2001)	1.6
Netherlands	27% (2005)	2.5

Figure 14 – Overview of cycling in a selection of European countries (Pucher and Buehler, 2008)

Within its Bicycle Master Plan implemented during the 1990s, The Netherlands focused on a wide range of issues including cycle infrastructure, road safety, mobility and modal choice, and employer engagement to increase commuting by bicycle. As a result 37% of journeys of less than 2.5km are made by bicycle, compared to just 2% in the UK (Pucher and Buehler, 2008). Large increases in cycling have also been achieved in Germany with annual cycled distances increasing from 17 to 24 billion kilometres between 1970 and 1997 (European Commission, 1999) with recent figures indicating a 14.5 % mode share for cycling in 2013, up from 9.5 % in 2002 (ECF, 2014).

2.5 Buildings, infrastructure and planning to support sustainable transport

Urban areas are not static with population, built environment and government policies that influence their evolution constantly changing overtime. The way in which buildings are positioned can influence how they will be used, their performance and the amount of energy used to move people between them. The infrastructure within urban areas has a very important role within the development of a city. Barton (2010) stated that *'the planning, design and management of the physical environment can enhance overall quality of life, promote social inclusion and husband natural resources'*. Conversely, infrastructure can have a detrimental effect on overall quality of life if poorly planned, designed and maintained. Jones, Marshall and Boujenko (2008) confirm that the existing street environment in the UK is unattractive for people on foot and that the street needs to be considered within the wider context, with design solutions based around both the place and the link According to De Jong (1986) motorised transport and its dominance over urban areas has *'differentiated and 'killed' the street. This began with the banishment of pedestrians to pavements and the widening of surfaces through demolition and infill of water courses. This was followed by installation of cables, pipes and rails for trams. Car use finally destroyed the roads equilibrium ending the social use of streets for street trades, processions and parades, childrens' games and celebrations and recreation'*.

Infrastructure supports buildings, including essential facilities and services such as roads, pipelines, overhead cables, reservoirs and other physical services are the most permanent features within the built environment, often having longer operational lives than individual buildings. Infrastructure is constructed and adapted to accommodate social, economic and environmental situations that develop over time and is usually dictated by technological developments. For example, the development and construction of the London Underground transport system during the late 19th and early 20th Century (Long, 2011), the erection of

electricity pylons in the 1930s to accommodate the development of electrification and the National Grid (Snow, 1993), and the widespread installation of mobile phone masts during the early 21st Century have generally been accepted by UK residents as part of the landscape of the country. Once installed, opportunities to redesign infrastructure on a large scale are limited and costly. Therefore careful planning and design at the outset and working with other organisations involved in infrastructure and the broader built environment can help to create more sustainable places. Infrastructure can shape the characteristics of an area and determine how people move around and use places. In some situations transport infrastructure can be adjusted to suit changing demands rather than investing in expensive new facilities at an early stage of development (Ortuzar and Willeumsen, 2011).

Patterns of travel in a city are affected by, and in turn help to form, the cities characteristics (Lapin, 1964). Transport infrastructure within the majority of UK cities is dominated by roads. In order to improve the sustainability of a city or region, roads need to become more accessible for more sustainable modes of transport. In most cities a degree of reorganisation of the existing built environment and the associated infrastructure is likely to be necessary to create a more sustainable transport system. The better informed the planning and design of this reorganisation, the more successful investment will be in creating a more effective and sustainable transport system. Marshall and Çalışkan (2011) evidence that a lack of integration between urban morphology and urban design creates urban places that are dysfunctional and that urban morphology and urban design should work together towards a common end. In many cases incorporating sustainable transport into existing urban areas may be difficult due to space constraints from the existing built environment. In many city centres the width between building facades provides a limit to the extent for improved cycle ways, particularly when attempting to accommodate other sustainable components including trees and green borders.

An urban scale approach to transport management is necessary to prevent the diversion from residential to arterial roads which occurred with Buchanan's 'environmental areas' approach of the 1960s (Ministry of Transport, 1963). Routes for circulation are only part of the physical built environment along with buildings and green spaces. Therefore a strategic vision is required which considers the needs of each user of the network. By using an urban scale approach, infrastructure needs to be combined with spatial, economic, legal, psychological and educational policy measures (Tolley, 1990).

Walking and cycling are two of the most accessible and sustainable forms of physical activity and are more likely to be dependent on neighbourhood design than other physical activities (Lee and Moudon, 2008). The Manual for Streets (DfT, 2007b) and its follow on Manual for Streets 2 (DfT, 2010b) define the way urban streets are designed, constructed, adopted and maintained in the UK. Among the key recommendations within these documents is the guidance to '*reflect and support pedestrian and cyclist desire lines in networks and detailed design*'. They recognise that transport strategies should not focus on traffic congestion reduction, but should prioritise economic regeneration, climate change, casualty reduction, reduced air and noise pollution, minimise the impact of transport on the natural environment, heritage and landscaping, and encourage more sustainable and healthy patterns of travel behaviour.

Research supports the argument that higher densities support more sustainable travel patterns and low carbon cities, as transport distances between centres is shorter, therefore enabling higher levels of walking and cycling (Newman and Kenworthy, 1999; Chen et al., 2008). Titheridge and Hall (2006) and Durand et al. (2011) found that dense, urban areas encouraged the use of public transport, cycling and walking and shorter journey distances. Stinson and Bhat (2004) have found that individuals residing and working in more dense and connected

urban areas are more likely to commute to work by bicycle. Smart growth is a concept that emphasizes density, diversity and design (Cervero and Kockelman, 1997). Lee and Moudon (2008) reported that uninteresting/utilitarian places within which to move created barriers for sustainable transport, and that urban design and planning practices can promote compact and mixed uses through locating restaurants, shops and banks in close proximity to residential uses. A compact, dense urban area provides conditions for efficient public transport whilst reducing distances needed to travel. This is supported by diversity of services, which reduces the need to travel long distances for frequent journeys, and design, which provides an attractive environment in which people want to be part of and to support. It has been suggested that employment densities at the destination are possibly more important than population density at the origin (home) (Ewing and Cervero, 2001; Chatman, 2003; Zhang, 2004; Chen, 2008). Therefore by grouping workplaces together, sustainable movement patterns could be focussed along well connected, common routes. Chen (2008) suggests that improving sustainable transport access associated with locations may be more effective than limiting car access.

Previous guidance in the UK recommended densities of newly constructed housing at national indicative minimum of 30 dwellings per hectare (dph) (DCLG, 2000). In 2010, the UK Government reissued its Planning Policy Statement PPS3 Housing, removing the national indicative minimum density of 30 dph from the previous version which follows the Conservative/Liberal Democrat Coalition Government's policy of '*putting power into the hands of local authorities and communities to make decisions that are best for them*' (DCLG, 2011). Density guidance is now based at a local government level providing flexibility to set density ranges that suit local areas as set out in the National Planning Policy Framework (DCLG, 2012). This framework aims to deliver sustainable development, but this will be dependent on how local authorities interpret it. The Framework does emphasize that local

planning authorities should support a pattern of development which, where reasonable to do so, facilitates the use of sustainable modes of transport.

With a 1% per annum replenishment rate of housing in the UK for 20 million existing homes (DCLG, 2006) there is little opportunity across much of the existing built environment to make significant change in housing density. The UK's historical trend for low density housing means that people are likely to have to travel further to work, making them more likely to opt for motorised transport (Newman and Kenworthy, 1999). Therefore changes need to be made to the layout and infrastructure associated with existing housing to make the transport changes required. Short distances between homes and shops, leisure facilities and workplaces make cycling and walking a more viable and an attractive alternative to motorised modes. Increasing mixed use areas by locating facilities within a shorter distance from each other present the opportunity to reverse this trend. Nucleated settlements where homes, shops, workplaces and recreation are located within a short distance from each other reduce the need to travel whilst also encouraging community spirit and community responsibility (Hudson, 1978). In a study in Northern California, USA, Handy et al. (2005) provided evidence that land use policies can support a reduction in car use and demonstrated that accessibility may lead to a decrease in driving if all else remains equal. They suggest that in new developments, mixed use zoning should be used to locate commercial and retail spaces within close proximity to residential areas and street connectivity ordinances that ensure direct routes between areas. In already developed areas, revitalisation of existing shopping areas, incentives for infill development, and redevelopment of underutilised shopping areas could encourage less car use (Handy et al., 2005).

Improvement of local access to key services and facilities increases social interaction and appreciation of the surrounding landscapes and built environment. The subsequent use of local

facilities such as libraries, shops, post offices and cafes stimulates the local economy, therefore maintaining local jobs and reducing pollution and congestion as fewer trips are made by car. For example *‘Local shopping centres flourish on streets with greatest connectivity and where footfall is high. In today’s economy this is very important to stimulate jobs and maintain community cohesion. Policy should work to increase pedestrian and cycle connectivity which would create new links and overcome the severance effect including heavy traffic’* (Barton, 2010). The choice to walk or cycle, together with the distance to travel, will also depend on the purpose of the trip. For example, it is very difficult to undertake a trip to the supermarket for a weekly food shop by foot or bicycle, whereas a daily walk to school or regular cycle to the workplace is possible for many people in urban areas. Therefore, appropriate planning and design of neighbourhoods can have a significant impact on modal shift by encouraging accessibility and reducing distances. This can enhance the appeal of sustainable transport methods, therefore encouraging the modal shift potential and the benefits that go with sustainable transport modes.

Cycling enables flexibility, providing freedom of route choice and timing, it is cheap, and can be relatively quick, particularly in urban areas. The environment experienced by cyclists includes buildings, public open spaces, roads, traffic, and other modes of transport. Good quality sustainable travel opportunities could be incorporated into all built environment changes, whether new build or refurbishment, through all stages of development including:

- spatial planning – utilisation of new or existing infrastructure, accessibility to new or existing services, novel modes of transport (e.g. electric bikes), attractive and safe sustainable modes of transport;
- design – car parking, density of buildings, bicycle storage, facilities at the workplace (e.g. showers) and encouragement of home working;
- construction – efficient project planning and procurement;

- utilisation/maintenance – bicycle sharing, car sharing, walking buses, limiting vehicles.

If cycling is left out at early planning stages of new developments, as well as in the detailed design and implementation, problems occur at many levels (Jones, 2001). For example, failure to recognise a bicycle as a vehicle can provide dissatisfaction with physical provisions whilst mixing pedestrians and cyclists can be hazardous to both due to the different travel speeds (McClintock, 2002). Cycling facilities should be considered with all transport related programmes, and the Chartered Institution for Highways and Transportation (2001) suggested that authorities needed to ‘*concentrate their efforts on raising standards, reviewing priorities, making selective modifications and providing occasional missing links rather than planning new networks*’, therefore indicating the importance of modifying and improving existing infrastructure. With regards to integrating cycling into urban areas, The Chartered Institution of Highways and Transportation (1996) recommended a hierarchy of solutions to encourage cycling:

- traffic reduction;
- traffic calming;
- improvement of junctions;
- redesign of carriageway;
- separate provision of cycle lanes and tracks.

This hierarchy has generally been supported and in 2008 the ‘*conversion of footpaths to shared use cycle tracks for pedestrians and cyclists*’ was added to the hierarchy (DfT, 2008b). Despite this hierarchy being designed to encourage cycling, it focuses heavily on motor traffic rather than making direct improvements for cyclists. Parkin and Koorey (2012) and Parkin (2010) confirm that this approach leads to changes to the existing network taking place at the individual route level, without understanding demand or broader engineering parameters that are pertinent to the cyclist.

Generally, guidance should be flexible rather than prescriptive, taking into account the contextual situation. For example, BREEAM certification (2013) and the Code for Sustainable Homes (DCLG, 2011) allocate 'points' for creating spaces for bicycle parking and in order to achieve high ratings these facilities need to be provided. This can cause problems at the design stage due to a lack of space for development due to high densities, and in other situations bicycle parking spaces are required in wholly inappropriate situations, such as at homes for older people where the majority of the residents are not capable of using a bicycle, with cycle parking only being used by visitors.

It is generally believed that the best way to travel is the quickest way, as presented by the CIHT (1997) which found that travel-time accounts for 80% of the costed benefits of road schemes. Therefore, changes in the built environment and the associated infrastructure need to be supported by a change in the way people think about mobility and this should be supported by policy.

2.6 Policy to support sustainable personal transport

The development and implementation of international, national, regional and local policies across government departments should be implemented to encourage an increase in the uptake of sustainable modes of personal transport such as cycling. Departments with responsibility for spatial planning including urban development, the environment, health, the economy and training and education should integrate cycling into their policies (European Cyclists Federation, 2011). Planners, architects and traffic, infrastructure and maintenance engineers are among many practitioners involved in transport planning in both the public and private sectors directly or indirectly. These parties need to be able to identify the links between cause and effect in transport decision making, as either providers of transport services or users

(Hensher and Button, 2008). Other groups and individuals such as the general public, councillors, charities and other voluntary groups may require guidance on how transport should be planned and implemented in order to persist with lobbying for changes to the built environment which encourage the use of more sustainable modes of transport.

Issues confronting policy makers have changed from accommodating transport infrastructure to managing transport (Hensher and Button, 2008) which requires a greater knowledge of the behaviour of people within the system. Policy relating to transport has become more complex interlinking many other areas including planning and urban design, health, air pollution, education, employment and sustainability/sustainable development. Policy instruments used within transport can involve changes in land use, infrastructure, management, information and pricing (CIHT, 1997) and policy development and implementation can have a direct or indirect impact on sustainable transport. For example, economic interventions such as congestion charging, parking controls and charges, fuel and vehicle taxes, road tolls and investment in public transport can influence the uptake of sustainable transport by providing a direct economic incentive or penalty to drive modal shift. Physical interventions such as the construction/widening of roads to better accommodate cyclists, increasing cycle parking facilities, improving public transport and making accessibility improvements for pedestrian and cyclists may provide the conditions for an increase in modal shift towards sustainable transport, but provide no direct incentive. Conflicts can arise between different policy areas. For example, even though many regions across the UK are actively encouraging the use of sustainable transport (e.g. via regional transport strategies), planning policy changes have eliminated both the limitations of parking spaces within new residential developments and the guidance encouraging high parking charges in town centres as the Government felt that drivers were being unfairly penalised (PPG3: Transport and PPG13: Housing) (DCLG, 2007). These changes are likely to encourage more car use rather than encouraging modal shift to more

sustainable options. These conflicts need to be recognised and remedied to ensure that impacts are minimised wherever possible.

Pedestrians and cyclists are often underrepresented in national and local government policies in the UK. Terminologies used add to the problem, with ‘transport’ being favoured over ‘travel’, where ‘transport’ implies mechanisation. In the EU Transport Statistics of 2011 the word ‘bicycle’ is only mentioned once (European Commission, 2011). Cycling policies need to be higher on the transport policy agenda and need to be coordinated with community wide plans, improved enforcement and taking opportunities to encourage cycling in wider strategies for health, air quality, leisure and recreation (McClintock, 2002).

2.6.1 UK policy and guidance for sustainable personal transport

The Buchanan Report (Ministry of Transport, 1963) brought together two subjects that had previously been treated separately; (i) the planning and location of buildings, and (ii) the management of traffic. Until this time the freedom provided by the motor car was seen as something to celebrate, with extensive plans for high capacity roads and motorways. The two components of the built environment considered by Buchanan, that significantly impact on each other, had traditionally been considered separately in their planning, design and implementation. The Buchanan Report Stated that *‘it is imperative that they should not be applied haphazard by different authorities reacting to different stimuli and following different timetables, but in a carefully coordinated way after comprehensive analysis and study of the whole complex’*.

The Transport Policy White Paper of 1977 (UK Government, 1977), for the first time, recognised the need to conserve oil supplies and the need to reduce dependency on the car

following the oil crisis of the early 1970s. It encouraged local authorities to consider ways to help cyclists, including cycle routes and special traffic lights. The White Paper provided a number of *suggestions* on how to increase cycling including the freeing up of side streets from all but minimum access traffic which could be designated to form cycle routes in urban areas. It also suggested that it might be possible to construct new cycle-ways in areas of open space or redevelopment. This policy document led to the development of dedicated cycle routes in cities such as Nottingham and Cambridge. However, the 1980s saw an increased focus on the car with the biggest road-building program since the Romans being introduced through the White Paper 'Roads for Prosperity' (Department of Transport, 1989) and a decrease in the numbers of buses due to deregulation.

Local Agenda 21 (LA21) (United Nations, 1992) was initiated at the Rio Earth Summit in 1992. LA21 was designed to encourage people to become involved in discussions about important issues in their area and all Local Authorities were encouraged to have LA21 strategies in place. LA21 was the first step towards localisation of decision making. Sustainable transport was a key issue, encouraging the giving of priority to cyclists, pedestrians and public transport. The Sustainable Development Strategy, released by the UK Government in 1994 in response to the Rio Earth summit, highlighted the need for dependency on the car to be reduced. This ethos was then incorporated into national planning guidance. For example, Planning Policy Guidance 6: Town Centres and Retail Development (PPG6) (DoE, 1993) encouraged the reduction of traffic through towns and recommended improved access and secure facilities for cyclists. Planning Policy Guidance Note 13 (PPG13) (DCLG, 2007) was a significant step forward as it encouraged the consideration of other forms of transport, including cycling, and to utilise forms of development that assist with their deployment. Local authorities were specifically asked to indicate that they were developing policies to make better provision for cyclists.

In 1994 The Royal Commission on Environmental Pollution recommended that 10% of all urban journeys should be by bicycle by 2005 (HMSO, 1994). This led to the launch of the National Cycling Strategy in 1996 (DETR, 1996) which was a key turning point for cycling in the UK with emphasis placed on cycling becoming a priority on the highways, in the centre of town, at the workplace and in new developments. Targets were set to double cycle use by 2002 and double it again by 2012, relative to 1996 levels. It stressed that more people want to cycle, especially for local trips, and that with safer conditions on the road a ‘critical mass’ of cyclists would be encouraged. The Strategy stated that *‘Cycling will feed on its success and make our streets safer and cleaner for everyone’*. Key objectives of the Strategy related directly to infrastructure including to *‘Achieve convenient cycle access to key destinations, reallocate road space to cycling and making the best use of existing infrastructure and resources to integrate cycling into other programmes’*. These policies to encourage the development of cycle infrastructure and guidance were produced by the Transport Research Laboratory on subjects including Cycling in pedestrian areas (Trevelyan and Morgan, 1993) to Trip end facilities for cyclists (Gardner and Ryley, 1997) and to Monitoring cycle use (Davies, Emmerson and Pedlar, 1999). Local initiatives were supported by the development of the National Cycle Network, established by the charity Sustrans in 1995. £42.5 million of National Lottery funding encouraged local authorities to invest in cycle routes, path networks and other cycle infrastructure in order to reduce car use, and to identify effective ways to increase accessibility by bicycle (Cope et al., 2003).

In 1998 the UK Transport White paper ‘A New Deal for Transport: Better for Everyone’ (DETR, 1998) stated that it wanted to improve the safety of vulnerable road users, including pedestrians, cyclists and motorcyclists, with a new system of funding for local transport and Local Transport Plans (LTPs), building on the LA21 concept and placing more emphasis at a local level which could be more specific to the context of the local areas. LTPs were to include

local cycling strategies, with some local authorities such as Oxford, York, Bradford and Edinburgh taking the initiative and developing long term cycling strategies. LTPs were to include maintenance of cycle lanes, speed restraint for traffic and adapting road space for more cycling facilities. Guidance for LTPs was produced in 2000 (DETR, 2000), 2004 (DfT, 2004a) and 2009 (DfT, 2009d). In the 2000 Guidance document, the DETR stated that *‘Land use planning is the most important long term solution to our transport needs at both strategic and practical levels. Good integrated planning reduces the need to travel and makes jobs and services more easily accessible for all....we need to change the way we plan, with a greater emphasis on enabling access by walking, as well as cycling and public transport’*. LTPs in England and Wales were required to include a 5 year strategy in their bids for capital funds to help deliver the transport requirements, which encouraged long term planning at a local level. The guidance provided for the delivery of the LTPs varied and enabled targets to be very loosely set, for example, ‘no reduction in cycle use’ was considered a satisfactory target (Golbuff and Aldred, 2011). Financial incentives were also introduced to encourage an increase in cycling to work, such as the ‘Cycle to Work’ tax incentive scheme introduced in the Finance Act of 1999 which removed the tax charge on green commuting benefits such as bicycles and associated safety equipment, together with a tax free business travel rate for cycling.

Planning Policy Guidance (PPG) notes, introduced through the Planning and Compulsory Purchase Act of 2004, provided the policy and guidance for the planning system in England. In Wales, Technical Advice Notes (TAN) provided advice to local authorities when producing development plans. PPG13 (DCLG, 2007) in England provided guidance on Transport whilst in Wales it was provided in TAN 18 (WAG, 2007). Although these were specific to transport, many of the other PPG and TAN documents provided guidance for areas relevant to transport, for example Tourism (TAN13, WAG, 1997), Planning for rural communities (TAN6, WAG,

2010) and Planning and affordable housing (TAN2, WAG, 2006). PPG6, Town Centres also had direct links with transport. PPG and TAN were replaced in 2012 as a result in the change in the UK government in 2010, as discussed below.

The Transport White Paper of 2004 (DfT, 2004b), became less target specific, stating simply that cycling should be increased and saw the abandonment of the National Cycling Strategy targets to quadruple cycling targets by 2014. A more direct approach was taken in 2005 with the funding of Cycling Demonstration Towns, to investigate how increased investment could increase cycling. Exeter, Derby, Brighton and Hove, Lancaster/Morecambe and Darlington each received £1.5 million over 3 years, with the smaller town of Aylesbury receiving £900,000 for the same period. Each town was invited to develop its own local strategy (Sloman et al., 2009). Findings showed an average cycling rate increase of 27% across the 6 towns in locations where automatic counters were located, and identified that occasional cyclists have increased the amount of cycling by 14% (DfT, 2009e). Reporting on this investment demonstrated the difficulties in collating and reporting statistics for cycling across urban areas. In 2008, an additional 10 towns and 1 city were incorporated into the Cycling Demonstration Towns initiative. Darlington, Peterborough and Worcester also received funding under the Sustainable Travel Towns initiatives to develop smarter initiatives to reduce car use. Initiatives proposed were more behavioural based ‘smarter’ measures such as marketing for public transport, development of travel plans and general walking and cycling promotion rather than a focus on infrastructure (DfT, 2010b).

With increasing levels of devolution across the UK, the scale of coverage for transport strategy and policy varies between different regions and urban areas. In Scotland the Scottish Executive is responsible for cycling policy and has an advisory body, Cycling Scotland, which implements Local Transport Strategies (LTS). In Wales, a regional based approach was

introduced in 2006 through the Transport (Wales) Act 2006. This saw the replacement of LTPs prepared by individual local authorities with Regional Transport Plans developed by four Regional Transport Authorities across Wales. An overarching Wales Transport Plan was set up by the Welsh Government in 2007, with the Regional Transport Plans published early in 2010. Cycling England was established in 2004, to deliver the National Cycling Strategy. Strategy papers were published in England, the first focussing on transport systems in general (DfT, 2007a), with the document ‘A sustainable future for cycling’ following a year later (DfT, 2008a). This focussed on specific areas to be targeted for investment including initiatives for schools, increased investment in cycling demonstration towns, and infrastructure associated with these. It also provided a cost-benefit evaluation of investing in cycling taking into consideration improvements in health, reduced congestion and pollution, and estimated the benefits to be 3.2 times the cost. In 2009, A Walking and Cycling Action Plan for Wales was produced (WAG, 2009) which contained a range of actions in cross cutting policies to change behaviour, create safe, attractive and convenient infrastructure, to include for cycling and walking, and to track progress through monitoring. Targets set included tripling the percentage of adults who travel to work by bicycle and for children cycling to school.

Both the English and Welsh strategies emphasise the requirement for interaction and funding to be provided from other sources as well as transport, such as health and climate change, to assist with funding of initiatives to increase cycling (DfT, 2005a). Cross-sector working between health and transport was highlighted in guidance produced by the National Institute for Health and Clinical Excellence (NICE) in 2008, specifically regarding the promotion and creation of built or natural environments to encourage and support physical activity. Recommendations were aimed at many settings and sectors including to ‘*ensure local facilities and services are easily accessible on foot, bicycle and other modes using physical activity*’, ‘*ensure pedestrians, cyclists and users of other modes of transport that involve physical*

activity are given the highest priority when developing or maintaining streets and roads' and to *'plan and provide a comprehensive network of routes for walking, cycling and using other modes of transport involving physical activity which should offer convenient, safe and attractive access to workplaces, homes, schools and other public facilities'*. Specific guidance was not provided on how to achieve these recommendations. In 2010 the Department for Health and the Department for Transport released the Active Travel Strategy, which emphasizes the importance of walking and cycling for short journeys (DfT and DoH, 2010).

The Conservative-Liberal Democrat coalition Government, which came to power in 2010, introduced a localised and decentralised planning policy approach, giving more power to local authorities. The National Planning Policy Framework (NPPF) introduced in 2012 (CLG, 2012) aimed to simplify the planning process. This current approach focuses on procedures for neighbourhood planning promoting community involvement. The Framework focusses on the promotion of growth and development rather than on conservation (Goodchild and Hammond, 2013). The simplification of such documentation can lead to a lack of guidance, particularly technical, and variation of interpretation of key core terms, such as sustainable development resulting in differences in practical implementation of the Framework across regions. This localised approach, however, supports Lumsdon and Tolley's (2001) suggestion that previous targets have failed to be achieved due to a lack of adoption of cycling strategies by local authorities. Decentralised responsibilities include road network and cycling infrastructure, stating that *'we believe it is local authorities that know their communities best, and can make the changes needed to encourage people to travel sustainably'* (DfT, 2011c). Decentralisation has also seen a change in funding approach with the Local Sustainable Transport Fund of £560 million over a 4 year period being introduced. This, together with the 'Linking Places Fund', were initiated to directly fund sustainable travel projects, particularly cycling and walking.

A key turning point with regard to the EU commitment to cycling was the signing of the 'Charter of Brussels' by 60 EU cities in 2009 which committed signatories to raise the level of cycling to 15% of all trips by 2020, among other cycling related targets. Notably, Bristol and Edinburgh are the only UK cities to have signed up to the Charter (European Cyclists Federation, 2009).

Through the implementation of appropriate policies and funded initiatives, levels of cycling can be increased significantly as has been demonstrated in Darlington, which has benefitted from the Sustainable Travel Town and Demonstration Cycling Town initiatives. Here, cycling levels increased by 113% over a three year period through the implementation of smart choice measures such as school training, promotion at schools, infrastructure changes to the pedestrian heart of the town, and development of seven radial cycle routes (DfT and DoH, 2010). Changes need to be made to all sectors of the built environment in order for these policies to be successful and for the targets they set to be met. Existing sustainable transport routes need to be well managed and new developments need to be carefully planned in order to achieve maximum effectiveness. The European Economic and Social Committee recommend that subsidy budgets should be available to develop and maintain cycling infrastructure (European Cycling Federation, 2011). The question is what should this funding be spent on? Focussing policies on frequent short distance journeys such as the work commute has the potential to make significant improvements on public health, traffic congestion alleviation and reducing emissions (Stinson and Bhat, 2004).

2.7 The journey to work

Travel to work is one of the most common personal travel movements, accounting for 16% of journeys (DfT, 2011a). It is undertaken by large numbers of people, requires substantial

investment in transport facilities to accommodate it and presents some of the most intractable problems to the urban transport planner (Tolley and Turton, 1995). It involves high motor traffic concentrations on certain routes at certain times of the day, producing high levels of motor traffic congestion. The UK census of 2011 (ONS, 2013) indicated that 760,000 people cycled to work, 2.9% of the population in England and Wales. 40% of cycling journeys are for work and business (DTLR, 2001) and cycling is a very real alternative to travelling by car to work within cities. 43% of journeys within urban areas in the UK are less than 5km (ONS, 2014) with commuters likely to spend half an hour or less travelling to work in major urban destinations (Neff, 1996). Pooley et al. (2011) reported that not all short trips can be made by bicycle or foot and that household interactions, the perception of walking and cycling not being the ‘norm’ and difficulties created by the physical environment impact on potentially higher levels. The routinely made, planned, relatively short distances travelled by a generally physically able population group make the journey to work an ideal focus for modal shift from the car to bicycle. Figure 15 illustrates the different journey speeds for different modes of transport in urban areas (European Commission, 1999).

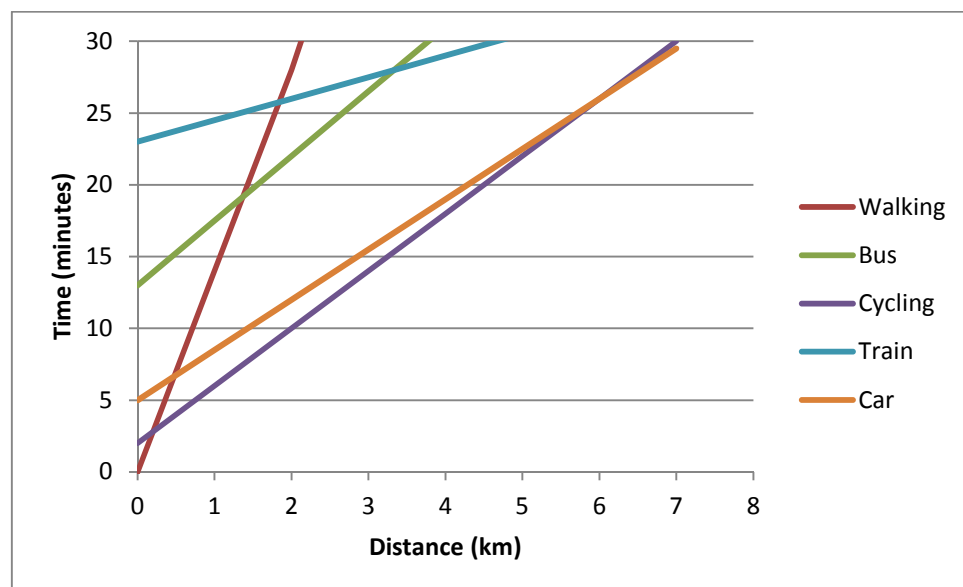


Figure 15 - Comparison of journey speeds for different modes of transport in urban areas (European Commission, 1999)

This demonstrates that in urban areas cycling can be as fast as travelling from door to door as travelling by car, and faster than other modes, particularly over longer distances within the urban area. Consideration of the journey to work is therefore key when planning changes to existing infrastructure or developing new areas. As early as 1944 Liepmann introduced city planning issues associated with the journey to work and stated that '*what is needed is to bring alternative workplaces within daily reach of every earner*' therefore increasing accessibility and ease of movement for all (Lapin, 1964). Liepmann's work focussed on new urban developments, as at the time vast expansion of UK cities was taking place during the post war phase. Thompson (1950) supported this work stating that '*decentralization should be intensified*' to remove the social implications associated with increased trip lengths and trip expense. In 1950 Thompson wrote '*the ideal is to have the workers place of residence within walking distance of his place of employment or, if he prefers it, within reach by a short bus journey*'. During this period however, social and employment mobility were very different than they are today with distances travelled to work being primarily short, taking little time and being predominantly made by foot or bicycle.

At the time of the Buchanan report in 1963 (Ministry of Transport) most locations of employment were found to be arranged in a limited number of groups, with a 'scattering in other parts of town'. However, the desire for a house with a garden and a concentration of industry and other forms of employment within city centre areas made it impossible to house enough workers near their employment. This, together with the post war housing emergency, meant that people could not find housing accommodation near where they worked. As mobility increased through the availability of the car and desire to live in the suburbs, the influence of distance between the home and workplace lessened. Up to the mid twentieth century the concentration of employment in, or close to, city centres produced radial commuting patterns, with morning and evening flows concentrated along rail, tram and bus

routes from main employment cores. Hudson (1978) reported that during the 1960s planners and engineers assumed the general availability of private and public motor transport when designing new housing developments to replace slum housing and to cater for the new growth in population. Land use patterns became more zoned according to function with housing estates, shopping facilities and industrial areas being separate from each other. This created a dependency on the motor car to get from one 'zone' to another. Out of town developments and replication of local services in dispersed groups further from housing have all encouraged the length of journey to increase. This pattern accelerated during the 1970s and 1980s in the UK. As the number of working women increased, the car became more affordable and the distance that people were prepared to travel in order to choose where they would like to live increased. The Chartered Institution of Highways and Transportation (CIHT) (1997) illustrated a change in the geographical pattern of journeys that took place between the 1970s to the 1990s with the traditional 'radial tip' pattern shifted towards a more peripheral, 'cross area' movement which reflected the change in land use patterns and distribution of employment and facilities such as shops and leisure. As Thompson (1950) had previously predicted '*the worst consequence of the longer journey to work is that people get used to it and so accept it as a normal part of city life*'. In the late twentieth and early twenty first century there has been some reversal of this trend with an increase in city centre living in the UK as a result of the conversion of industrial and commercial buildings into apartments.

Pinjari et al., (2007) investigated causal effects relating to the selection of a place to live based on lifestyle preferences, attitudes and values. The research was undertaken to support the merits of altering the structure of the built environment in order to change travel behaviour. It was found that householders locate themselves in built environments which suit their lifestyles, which include residential location and travel options, and that modifications to the

built environment can bring about changes in transport mode choice, when controlling for residential sorting effects (Pinjari et al., 2007).

Wardman et al. (2007) found that if topographically flat, compact cities could be made safe for cyclists and estimated that approximately 43% of journeys to work could be made by bicycle. In Copenhagen 55% of commuters' cycle into the city centre and are encouraged by off-road routes *beside* all main roads in the city centre (Jensen, 2013). Predictive modelling by Wardman (2007) found that by introducing *non-segregated* cycle lanes on around half of the routes to work on minor and major routes, cycling rates would increase by 14%, whereas by converting an entire network to *segregated* cycle ways there would still only be 21% growth in cycling to work which would be a relatively small additional impact considering the financial input that would be required. It was found that a package of measures including modest financial incentives, improved facilities on half of the journey and good facilities at work, would be the most effective means of increasing cyclist numbers (Wardman, 2007). In a survey of 1,941 people Caulfield et al. (2012) found that 56% of respondents stated that more connected on-road cycle lanes would encourage them to begin to cycle to work, that all respondents had a preference for cycling on routes with lower motor traffic speeds, and that direct routes with short journey times were the most important variable for existing cyclists.

2.8 Infrastructure for motor traffic and cycling at an urban scale

A well designed cycle route should aim to improve the quality of a cycle trip, reduce the likelihood of being involved in a road traffic accident, and create conditions such that more people will choose to cycle (DfT, 1995). Drivers of motor vehicles are provided with a network of continuity making their movement straightforward, as roads are interconnected at every street junction (Ramsay, 1990). Conversely, cycling levels have been suppressed by the lack

of facilities and by poor road traffic conditions (Hopkinson and Wardman, 1996). The existing road network, with careful management and maintenance, could provide an ideal cycling facility within urban areas. Cyclists can mix well with all vehicular traffic at speeds below 20 miles per hour (mph), can mix with most vehicular traffic between 20 – 30 mph (unless there are significant Heavy Goods Vehicles), can mix with some segregation from vehicles travelling between 30 – 40 mph, with complete segregation being necessary where vehicle speeds are over 40 mph (CIHT, 1997). Litman (2000) illustrated that improvements including traffic calming devices, traffic humps and street trees can help to improve modal shift through small scale land use changes.

Highway networks connect the residential, commercial and industrial urban and suburban areas of cities, towns and villages. The interrelated nature of the network means that a change to one part will have implications on other parts of the network, and therefore potentially on the modal share. This interaction between different components and users of a transport network needs to be modelled in order to identify, quantify and understand these knock on effects. Roads are classified into hierarchies to enable the provision of appropriate guidance on their design, maintenance, location and use. In the UK the Highways Agency manages the Strategic Road Network in England (Highways Agency, 2013) which consists of motorways and major trunk roads, which are either illegal or not user friendly for cyclists. In Wales and Scotland, motorways and trunk roads are managed by the respective devolved Governments (Highways Agency, 2013). The upkeep and management of all other roads including ‘A’, ‘B’ and minor roads is undertaken by local highway authorities. A road hierarchy reflects the use and behaviour of the road, and this relates to the design of and features provided on that road. Variable features can include width of the lanes, footpaths, lighting, speed limits and road markings.

Other classifications exist including ‘Functional Hierarchies’ which are used to categorise actual or intended use within the network as a whole as an aid to design, adaptation and management. CIHT (1997) suggested that a ‘functional hierarchy’ should provide for a mixture of transport and non-transport uses and should support the idea that a motor vehicle should intrude as little as possible into neighbourhoods. With newly designed or redeveloped areas the implementation of functional hierarchies is possible, however, in built up areas where the existing network is likely to have developed over time their application may be more problematic. The Design Manual for Roads and Bridges provides the general principles for the design and assessment of highway networks in urban areas within 15 Volumes (DfT, 2008c). At times compliance with guidelines is difficult, particularly in dense historical urban areas, due to the characteristics of the existing built environment.

Wardman et al. used a classification system for cycle provision (2007) as follows:

- segregated off-road;
- segregated on-road;
- non segregated on-road;
- major road with no facilities;
- minor road with no facilities.

In 1977 the UK Government Transport White paper stated that ‘*completely segregated routes would be impractical or far too expensive in most cities*’. Common constraints for off-road routes in the UK include a lack of space and finance. Providing consistently substandard solutions can put cyclists at more risk than if no provision was made at all (McClintock, 2002). Therefore compromise is required to provide facilities that are fit for purpose and meet the needs of all transport network users at an appropriate financial cost.

Sustrans has attempted to stimulate the uptake of segregated off-road routes through the promotion of ‘Greenways’ which are located along features such as railway paths or canals (Sustrans, 2007). A ‘Greenway’ should be designed to reach the centre of an urban area by continuing along lightly trafficked roads rather than ceasing at a location away from built up areas, which features often utilised as cycle paths such as unused railway paths or canals typically do. It is suggested that a popular ‘Greenway’ should be continuous over its whole length as breaks in the route, particularly severance caused by a heavily trafficked road, will reduce the use of the route. The Greenways report (Sustrans, 2007) stated that pedestrianised town centres are very often the greatest obstacle to encouraging cycling in a town and that solutions must be devised for every potential barrier along the whole length. It is proposed that the final element of the ‘Greenway’ is the ‘Green Street’ which comprises sections of the continuous route located in built up areas which should consider the needs of both the pedestrian and cyclist, and continue along attractive, memorable and safe routes. It is recommended that ‘Green Streets’ should be located on a lightly trafficked and slow speed roads where the invasive presence of vehicles is diminished, providing cyclists with a short cut to the urban centre (Sustrans, 2007). The guide to providing ‘Green Streets’ recommends:

- level routes, rather than dropped kerbs;
- attractive streets with addition of greenery on both the road side and the properties;
- open places to pause, sit and talk including graveyards, landscaped areas around public buildings and playing fields;
- home zones (Biddulph, 2003) where streets have been rearranged to be more pleasant;
- raised road crossings;
- opening of pedestrianised areas out of peak hours;
- space taken from the road or widening of a footway for shared use with pedestrians.

On-road cycle lanes increase the perceived safety for cyclists by increasing the overtaking space afforded by motorised traffic and this is likely to increase the frequency with which experienced cyclists use the route and encourage some more confident new cyclists. However, the effect on encouraging significant numbers of new cyclists is likely to be limited as new or inexperienced cyclists will still be intimidated by the proximity of heavy traffic especially if there is a lack of infrastructure and dedicated routes for cycle traffic (Krizek and Roland, 2005; Clayton and Musselwhite, 2013). Buehler and Pucher (2011) reported from a study of 40 US cities that bike paths and lanes had significantly higher rates of commuting than cities with few facilities, supporting the development of bike focussed networks.

The requirement and provision of new infrastructure for cycling should be evaluated in detail at the early design stage. The impact of inappropriate cycle network design is demonstrated by the 200km cycle network in Milton Keynes in the UK developed in the 1980s. Although the network was completely separated from the road system, user surveys found that the network provided poor personal security, was badly designed and poorly maintained. Routes ran through green spaces which afforded little security to users and were more difficult to maintain than those adjacent to main roads. The network was developed more for occasional leisure purposes rather than for cycling to and from work on a daily basis (Franklin, 1999).

A staged approach to the development of a cycle network has been taken in Edinburgh with investment made into off road routes along old railway lines during the 1980s which created a fragmented network. Cyclists were willing to divert from well-connected roads onto off road routes and, over time, the connectivity of routes has improved. On road cycle lanes together with Safe Routes to School schemes were subsequently developed which created a city wide joined up network (Williams, 2002). Cyclist numbers increased from 1.4% in 1981 to 4.9% in 2011 (City of Edinburgh Council, 2011). One of the key aims of the current travel action plan

for Edinburgh is to prioritise the missing or sub-standard links in the network such as poorly surfaced sections of paths and reallocation of road space, which the City identify as minor changes that can make a big difference. The Scottish Government, through its Guidance Document for Practitioners, *Cycling By Design* (Transport Scotland, 2011), recommends to take the network approach from the start and provide a network planning guide.

One of the most successful attempts in Europe to increase cycling across an urban area took place in Delft in The Netherlands which proposed a network of cycle facilities as part of the Delft Cycle Plan in 1979 (Department of Transport and Planning, 2011). Three network levels were developed to meet the needs of different levels of cycle traffic:

- Town level – a grid that connects major destinations within the city located 400 – 600m apart. This included the construction of large bridges and other infrastructure to cross barriers such as railways and rivers;
- District level – a grid of 200 – 300m linking the town level grid and also strategic points within the district such as schools. This used less costly and less sophisticated facilities such as cycle strips (textured and coloured areas marked for use by cycle traffic) and small bridges;
- Sub-district level – providing links in residential areas to higher level routes.

The aim was to provide coherence across the city, particularly reducing door to door journey times. The network approach was more successful than expected and the programme provided evidence that a cohesive, joined up network promotes cycle use and that expensive facilities are not required on all routes. Studies of the programme by the Ministry of Transport (1986 and 1987) found that overall mobility did not decrease, confirming that the development of the cycle network did not have a detrimental impact on mobility. In areas where the cycle network was improved, cycle trips increased from 6-8% and trip lengths by bicycle also increased as destinations further away came within reach by bicycle due to improved links.

The study also demonstrated that improvements in the coherence and quality of the network resulted in positive changes in route choice. Hartman (1990) concluded that *‘through providing a network with a fine grid and good continuity the need for detours is reduced which are not favoured by cyclists, and that origins and destinations across the whole city become within easy reach. Measures do not need to be expensive but should aim to provide continuity. Expensive measures should focus on high level routes, where they are more cost effective as they will attract a higher volume of bicycle traffic’*. This example demonstrates how a masterplan approach should be taken rather than focussing on black spots. By taking a coherent approach, a ‘mental map’ of a route can be generated enabling distances and times to be assessed which can influence the decision making process associated with modal choice. These all need to be brought together by the local authority and promoted on a regular and consistent basis.

Few detailed studies are available that estimate the demand for cycling facilities (Goodman, Sahiqvist and Ogilvie, 2014; Law, Sakr and Martinez, 2013; Titheridge and Hall, 2006; Hopkinson and Wardman, 1996) together with the economic benefits that these can provide. Justification to undertake costly infrastructure changes are required to evidence value for money, particularly in austere times. In 1996, Hopkinson and Wardman compared the full range of costs associated with the implementation of four cycling infrastructure schemes in Bradford, UK, including construction and maintenance, and they compared this with benefits including time savings and safety improvements. Table 1 shows estimates of the current number of trips, the monetary value associated with improved facilities and the future use of each route after investment.

Table 1 - Cost benefit evaluation of four cycle schemes in Bradford, UK (Wardman and Hopkinson, 1996)

Scheme	Current weekly single trips	Value per single journey (pence)	Future weekly single trips	Present value of benefits (PVB) (£)	Cost (£)
Canal Rd - widened lane	572	18	841	74,000	333,000
Canal Rd – segregated path	572	30	1027	140,000	77,000
Manningham Lane – bus lane	1110	7	1194	47,000	0
Free cycleway	n/a	71	1480	307,000	250,000

Cost estimates for Canal Road were obtained from the clients. No cost was allocated to the bus lane as there was no additional cost to, or as a result of, the cyclist. The cycleway costs were based on figures from Shayler et al. (1993) based on new tracks. It can be seen that the present value of benefits added for the widened lane does not cover the costs of the works. The other 3 options all generate more value than the cost and therefore can provide a good return on capital invested even in areas of low cycle use. This data has been utilised within the development of Webtag (DfT, 2014a).

Most cycle design guidance in relation to route choice in the UK has been based on Dutch Cycle Design Guidance (CROW, 2007) which identified the following fundamental criteria for urban cycling routes:

- Coherent – linking major trip origins and destinations; continuous and consistent in quality;
- Direct – based on desire lines, and that detours deter use;
- Attractive – on subjective and objective criteria such as lighting, safety and aesthetics;

- Safety –minimise danger and casualties;
- Comfort – well maintained surfaces, gentle gradients and designed to minimise complicated manoeuvres and interruptions.

This guidance combines features of a journey associated with the source, route and destination together with infrastructure, geography and interaction with other route users, all of which can be influenced with careful planning and design. Parkin (2007) stated that cyclists are likely to accept a trade-off between these characteristics, for example to trade a lack of directness for enhanced safety, with others favouring a more direct route with a quicker journey time.

In an attempt to support the changes required to the built environment research has been focused on mode choice and particularly the infrastructure most likely to encourage more cycling. A survey by Lee and Moudon (2008) found that ‘sufficiently active’ people lived in environments with more supportive infrastructure for active living, including smaller street blocks, fewer motor traffic lanes and slower traffic speeds. Participants agreed that there were more people cycling in their neighbourhood, which although might be perceived rather than actual, provides encouragement to others to start/continue cycling. Overall they found that interventions from small changes including more lighting and benches to longer term interventions which include street layout and land use practices had a positive impact on increasing cycling (Lee and Moudon, 2008). Guthrie, Davies and Gardner (2001) found attractiveness of the route and smoothness of the road surface to be two of most popular features of a cycle route whereas Westerdijk (1990) found distance, pleasantness and safety were the most important criteria.

Wardman, et al. (2007) suggested that a three-fold increase in cycle share and a reduction in car commuting trips by 13% could be achieved if policies were developed around a package

of measures which included enabling cyclists to complete at least half of their journey to work on a dedicated cycle route with associated facilities, providing good facilities at work (e.g. cycle parking, changing facilities) and offering a financial incentive of £2 per day. This should be supported by improvements at junctions, localisation through land use planning and road pricing (Wardman et al., 2007).

2.9 Connectivity and accessibility

Connected neighbourhoods are essential for vitality, viability and choice, with links between activities and places helping to ensure success (Barton, 2010) with good access, into and through spaces, creating interesting places (Brownhill and Rao, 2002). Iacono et al. (2010) stated that the concept of accessibility offers a basis for the development of sustainability policy relating to the built environment and travel which can be supported by detailed, reliable metrics to assist with making sounder decisions when providing for non-motorised transport. Accessibility focuses on the distance between the origin and the destination together with the stresses created by the adjoining environment. Lin and Yu (2013) identified that previous research looking a network design focussed on traffic needs rather than on non-motorised transport with accessibility research limited by the data and tools available (Stähle, 2012) and that methods for measuring distances between places is restricted (Kwan, 2003).

In 1974 the Independent Commission on Transport (ICT) concluded that '*the real meaning of mobility or the true goal of transport is access*'. Mobility depends on the personal situation including health, finance and facilities available which are in turn influenced by a complex combination of social, economic and environmental factors. Improving access allows unconstrained journeys which can be made at any time, in any direction by sustainable modes of transport, and is more easily influenced through sustainable transport policies. The

Buchanan Report (Ministry of Transport, 1963) stated that *'the design problem, essentially, is a matter of rationalising the arrangement of buildings and access ways..... The basic principle is the simple one of circulation'* and utilised the example of a hospital to illustrate the concept of a complex traffic problem where a lot of people, equipment and other items need to be distributed to multiple locations. The principle is based on the creation of 'areas' of environment - wards, operating theatres, kitchens etc. - which are served by corridors. Although movement takes place within each environment, they are not opened up to through traffic, which would result in a fundamental error in circulation planning - for example, food trolleys are not pushed through operating theatres. It was suggested that there should be *'urban rooms'*; where people can move around without the hazards of traffic, with complementary networks of roads (urban corridors), for primary distribution of traffic to the environmental areas. It can be argued that by allowing all modes of traffic on all streets, motor traffic is dispersed so that no street is too busy and circulation enables security for all through visibility. However, by designing streets with no access to motor vehicles, cyclists and pedestrians have safer routes to travel as streets closed off to motor traffic are quieter and less polluted, and from a financial perspective funding for public transport and motor traffic can be allocated to maintain distributor routes (European Cyclists Federation, 2011).

Rybarczyk and Wu (2014) have developed a discrete choice model to examine built form factors such as density, bike facilities and slope. They found that built form factors that enhance visibility and connected street networks significantly affect bicycle mode choice and decisions made at the trip origin. They conclude that the design of the built environment plays an important role in the cycling as a mode of transport. Jones (2012) identified that cycle route users support measures along existing road networks that connect them to everyday activities. This supports the concept of 'Filtered Permeability' which restrains car use, creates a denser network for non-motorised transport and provides advantages to cyclists such as exempting

them from access restrictions applied to motor traffic or through the creation of short connections only available to cyclists and pedestrians (TCPA and DCLG, 2008). The principals of 'Filtered Permeability' have been applied to residential development areas in cities such as Vienna and Hamburg, but these were in new developments which excluded cars from development areas from the outset (Melia et al., 2013). Application to existing residential areas has been more limited, with Groningen in The Netherlands being the largest case in a city centre area with over 16,000 residents (Melia et al, 2013). In Groningen, motor vehicle traffic is channelled onto a limited network of main roads, and short cuts such as bridges and tunnels are provided for sustainable modes of transport. Initial findings by Goodman, Sahiqvist and Ogilvie (2014) have found from a pre and short term post study related to the construction of new Pont-y-Werin Bridge in Penarth near Cardiff that more connected local routes generated new cycle trips in the long term.

In the UK an increasing use of hierarchical layouts has seen an increase in cul-de-sacs which prevent through flow of traffic and an increase in journey length, encouraging a greater amount of travel by car. Routes for cyclists that are unnecessarily unconnected can add significant distances onto journeys making cycling less of a favourable option. Cul-de-sac layouts also demonstrate a lack of intelligibility with spatial form as recognised by Hillier (1987) who identified that places are so ordered and similar that they lack legibility when moving around them.

Accessibility can also be improved by two directional cycling on one way streets as was piloted in Kensington and Chelsea where a 'No Entry Except Cycles' sign was trialled to help inform the potential for wider application of this new sign. Video footage analysis showed that there was an increase in the number of cyclists travelling along the newly signed road and that motorists were compliant with the 'No Entry Except Cycles' sign (Sewell and Nicholson,

2010). In the Netherlands, 'home zones' were developed in order to create fine networks of routes to establish a cycle friendly infrastructure (Grotenhuis, 1978). A key feature of a 'home zone' is that they enable connected and permeable networks of streets for sustainable modes of transport. A study in Denver, Colorado by McKay (1995) found that through identifying likely travel corridors for cyclists, a safer infrastructure could be provided by integrating cyclists and motorists whilst concentrating cyclists on common routes to make them more obvious to drivers.

Connectivity provides more and shorter routes to destinations (Moudon et al., 2006, Randall and Baetz, 2001), providing continuous bicycle facilities away from motor traffic which are favoured by users (Sener et al., 2009; Caulfield et al., 2012). A study across four cities in the UK (Barton, 2007) found that aspirations regarding liveable neighbourhoods are surprisingly consistent amongst people with different lifestyles. Barton found that directness of the route network provided was directly related to how far people will walk and cycle. It was identified that neighbourhoods should link to the wider city and region, creating a permeable and connected environment with real network choices (Barton, 2007). Sallis (2009) identified that improved street connectivity was believed to increase walking and cycling compared to neighbourhoods with long blocks, few intersections, and dead ends.

In Buxtehude, Germany, a holistic planning approach to connectivity has been used by mapping all lines of direct connection between key origins and destinations for cyclists (Döldissen and Draeger, 1990). This generated a direct connection map which was superimposed onto existing street maps to estimate approximate traffic loads. Pre-works studies indicated that journeys to work by foot or bicycle were much lower than the average for all journeys, and that journey speed was lower than the national average. Following traffic counts, it was found that there were serious breaks in cycle connections at locations including

pedestrian only bridges, one way streets and pedestrian only precincts (Döldissen and Draeger, 1990). Subsequent improvements, made as part of the Tempo 30 scheme, included reducing traffic speeds to 30km/h on subsidiary roads together with measures to improve pedestrian and cycle transport. Connections were improved by new bridges, cycle paths against one way streets, a well-designed subway under a ring road, and opening up of the pedestrian precinct for cyclists. Opening up of the pedestrian precinct was supported by campaigning, signpost design and by providing a central carriageway for cycles within the street layout to reduce conflicts. Bicycle streets were also identified which were only able to be used by motor vehicles by residents or visitors to residents. Attractive and inexpensive measures including road narrowing, signage and reduced parking were implemented in these locations (Döldissen and Draeger, 1990). The changes have seen an increase in cycle traffic of 27% (Davies, 2001).

The choice that a cyclist makes when deciding what route to take can be based on many different factors and also the type of cyclist that is making the decision. Being able to understand and forecast the route choice made by individual cyclists can assist in positioning appropriate infrastructure in the most suitable locations. Parkin, Wardman and Page (2007b) investigated perceived risk and route acceptability studying the video clips of the movement of cyclists. This research has resulted in a risk model that quantifies the effect of motor traffic, and road features such as roundabouts and junctions which can assist with specifying infrastructure improvements, recommending routes of least risk and assessment of accessibility for cyclists. Findings indicate that the presence of facilities at roundabouts and junctions generally have not had an effect on the perceived risk or acceptability of cycling and that the presence of facilities might even suggest to cyclists that the junction is more risky than they may have perceived it to be. Transport for London (2012) have investigated the decisions that cyclists make in London when choosing a route and the importance of different route features. The survey involving over 2,000 cyclists revealed that avoiding motor traffic is a key

consideration for route choice. The survey also revealed that cyclists would prefer to cycle in a cycle lane and in green spaces/parks even if it meant a longer journey. Cyclists were willing to take a significant detour to avoid junctions considered unsafe. Global Positioning System (GPS) has been used to investigate route choice by Broach, Dill and Gliebe (2012) where 164 cyclists were observed in Portland, Oregon over a period of several days. Findings suggest that cyclists are sensitive to distance, number of turns, slope, presence or absence of traffic signals and volume of traffic. They also illustrate that off-street bike paths and enhanced routes with traffic calming facilities are highly valued. Work by Hopkinson and Wardman (1996) and Stinson and Bhat (2003) indicated that cyclists prefer quieter routes whereas Barton (2010), Caulfield et al. (2012) and Law et al. (2013) found that many cyclists will use a busy road if it is the most direct route, even if less direct segregated cycleways are available. Law et al. (2013) also found that accessibility overrides comfort throughout a daily period. Caulfield et al. (2012) reported that infrastructure type, the number of junctions, traffic speed and the volume of other cyclists are also key variables in determining route choice, with routes with no facilities or that have a bus/cycle lane are the least favoured cycle route types. Jones (2001) confirmed that issues such as conflict with pedestrians, lack of continuity, poor surfaces and inconvenient routes all potentially exist on motor traffic free routes, and that these need to be eradicated if quieter routes are to be promoted for cycling. Much of the work on route choice focuses on aggregate studies and general infrastructure availability (Handy, Van Wee and Kroesen, 2014).

The UK Government's Accessibility Initiative (DfT, 2012c) provides guidance to local authorities in England on three main network indicators: travel times (shortest time to reach the desired destination), destination indicators (proportion of users that can access the services within a certain time) and origin indicators (number of sites available to users in a particular area). Accessibility statistics are measured for eight key services including employment

centres, schools, hospitals and food stores. This information has been collected since 2005 to help local authorities to develop accessibility strategies. Information is collected for journeys made by public transport, walking, cycling and by car, and is collected at local authority level and Lower Super Output Area (LSOA). Data for cycling was obtained from the Integrated Transport Network which includes cycle paths, road class, nature of the road and road routing information. Figure 16 illustrates the time taken to reach key services in England by bicycle. By 2011, in urban areas most key services could be reached by bicycle in just over 10 minutes, with the exception of hospitals, which took an average of 21 minutes (DfT, 2012d).

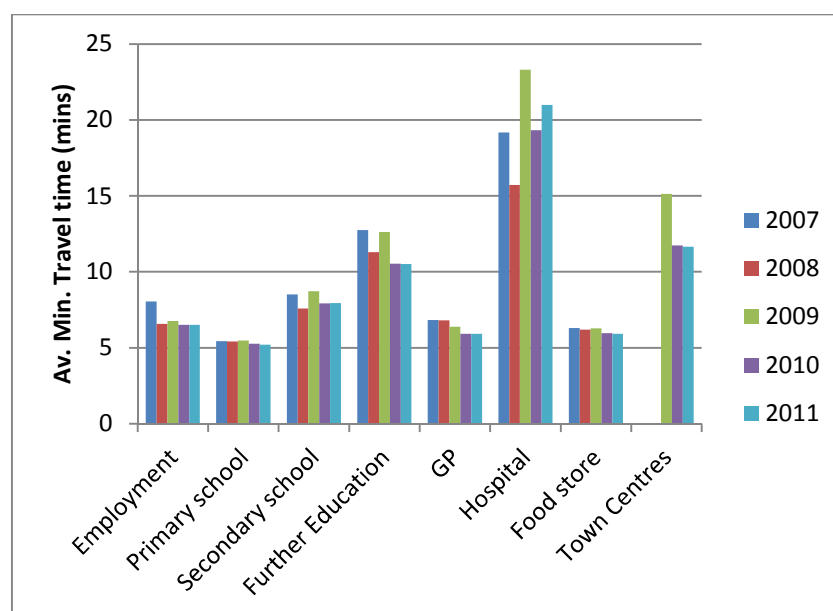


Figure 16 - Average minimum travel time to reach the nearest key services by bicycle, England, 2007 - 2011 (DfT, 2012d)

Strong design strategies are therefore needed to increase connectivity and accessibility and, therefore, network demand for cyclists (Lee and Moudon, 2008). Appropriate layout of infrastructure is essential to allow ease of movement which should be supported by a clearly understood built environment together with an understanding of the needs and preferences of people and their behaviour. Cycle routes should not be located only where an opportunity arises; the aim should be to actively connect places in an informed way.

2.10 Transport modelling at an urban scale

Complex movement patterns are created within urban areas as hundreds or thousands of individual movement decisions are made every day by different modes. The mode that these journeys are made by and the route that they travel will have a profound implication on the density of traffic within a network, the infrastructure required to support it, and the quality and convenience of the journey (Tolley and Turton, 1995). Travel decisions are made based on time of travel, route, mode, destination, and frequency or trip suppression and the cost of the alternatives (Bates, 2008). The transport system is dynamic and models need to reflect this, to take into account the changing nature of people's behaviour and infrastructure over time and through space (Kitamura R, 2008; McNally and Rindt, 2008). It is highly advantageous, through modelling, to be able to predict the likely travel situation from the present time to a number of years into the future, as this information can provide the basis for economic evaluation of proposals and can help establish value for money in absolute or comparative terms (CIHT, 1997). Transport modelling describes and predicts the movement of people and goods in a given or future environment (Axhausen, 2008). Models seek to identify key relationships, not necessarily to replicate the entire transport structure and focus on the simplification and abstract importance of underlying relationships (Hensher and Button, 2008) and aim to improve analytical capabilities and impose distinct and repeatable working practices (DfT, 1995). Modelling is required to support simple and involved measurements and create awareness of progress towards targets. Many transport modelling techniques are acquired through 'trial and error' over long term periods of development and detail of the validation process are often not fully documented (Smith and Blewitt, 2012).

Transport modelling was developed in the USA during the 1950s and first implemented in the UK in the 1960s, with progress being evolutionary rather than revolutionary (Hensher and

Button, 2008). Reasons for modelling have changed, with initial concerns lying with providing enough capacity for increasing demand for motorised transport, and a more recent focus on restraining further growth and limiting impacts on the environment (Bates, 2008). Traditional peak hour modelling is no longer as relevant due to changes in lifestyles, longer shopping and business hours and logistics (Bates, 2008).

The complexity and detail of a model should reflect the scale and objectives of its use. For example, specific cycling and walking schemes can be small and therefore the amount of effort that can be allocated to their appraisal needs to be proportional to the scale of the project and its impact on active transport (DfT, 2014). Models need to be reliable and to be trusted by users to provide useful results, and appropriate and suitable validation needs to be undertaken to achieve this. Issues that arise in modelling transport include the time period which to consider, the geographical area/form to represent the origin and destination, the modes of transport to be considered, type of person making the movement and the purpose for which the journey is made (CIHT, 1997). The movement of passengers and goods by various modes of transport can be modelled including car, bicycle, bus, aircraft, boat, lorry and train together with movement on foot. Models can be used at different scales from individual junctions (SCOOT model, Robertson and Bretherton, 1991; TRL, 2013), through to regional (SATURN; Van Vliet D, 1982; Atkins and ITS, 2013) and national (NTM; DfT, 2013c), and investigate different aspects associated with transport, for example congestion and pollution (Berkowicz, Winther and Ketzel, 2006). The function of the model will determine the type of input and validation data collected. For example, a model required for assessing energy consumption will require outputs of travel distances and numbers of vehicles that can then be associated with emissions (Pinho et al., 2010).

Spatial separation is the driver of travel demand (Bates, 2008). The spatial unit used within modelling is very important to enable travel alignment, defined as the allocation of travel units to each link in the network, particularly when considering active transport modes such as cycling and walking (Willumsen, 2008). Origins and destinations may correspond to a specific building or zone according to the level of aggregation being used within modelling (Willumsen, 2008) and these will be connected by links and nodes. Using larger geographical areas for the origin and destination, for example a ward or purposely created zone around an intersection or point source, can lose a level of precision and as such non-motorised transport should be assigned smaller aggregation units (Iacono et al., 2010). For example, Berrigan et al. (2010) used GIS based Arcview with studies based at a block level with circular ‘buffers’ around respondent addresses. The SATURN model (Van Vliet, 1981; Atkins and ITS, 2013) is based on nodes (intersections) and arcs (roads) which link the nodes. A major component of transport planning is the distribution of trip generators such as housing, destinations such as employment centres, together with other factors such as levels of employment, health and other population trends (Tolley and Turton, 1995). Potential reduction in model accuracy also applies to distance measurements, with the Euclidean (as the crow flies) distance between origin and destination (Titheridge and Hall, 2006; Chen et al., 2008; Wells et al., 2007) being used as a measure of distance rather than actual route length. Stigell and Schantz (2011) confirmed that distance is critical in transport studies and investigated methods for measuring active commuting route distances. They found that straight-line distances underestimated the criterion distance (commuters’ self-drawn route measured with a curvimeter) by an average of 21%, although this figure does decrease with distance. They found that GIS distance calculations overestimated distances by 12-21% and confirmed that this was due to walking and bicycling paths not being included on GIS maps. Urban form can impact on the ability to model an area, for example, dense urban areas with a radial network with one central area are simpler to model than dispersed areas. Rivers, major roads and railway lines that concentrate

flows also have an impact on movement patterns. Areas which are considered to have more attractive cycling qualities such as lots of minor roads or space available for off road facilities require more complex modelling. This is also true of more rural locations, dispersed areas or a grid street pattern with no main centre (DfT, 1995).

Transport research is heavily dependent on data, and in many applications time and cost restrain the ability to gather data at the level of detail needed for research (McNally and Rindt, 2008; Iacono et al., 2010). Traditional large scale demand models are time consuming and expensive to produce, mainly because of the large amounts of reliable, baseline data required. Data collection is expensive often requiring expensive equipment and time to collect, collate and analyse (Iacono et al., 2010), therefore needing to be carefully planned and designed to minimise cost and maximise the effectiveness. There are therefore limitations in availability of general, widescale flow data. For example, The Department for Transport provides street level motor traffic flow data for a number of locations in the UK which are accessible to the public (DfT, 2013f). The location of data collected is presented on an interactive map and is broken down into different modes for each region. Data collected varies across regions, for example, for data for Cardiff was available for 59 data points since 2005. On viewing the detail of the interactive map, these data points were positioned at 17 locations and data was only available as an annual flow figure for each location and is therefore of limited use. Data used and the model selected will depend on the reason for using a model, together with the data availability (Ortuzar and Willumsen, 2011). For example, investigating the impact of large price changes on the use of public transport will require income data (Bates, 2008). With regard to resources, utilisation of existing data sets is better for financial and time reasons, however, updated data sets will be required in order to make the most reliable predictions.

When considering designing for pedestrians the Chartered Institution of Highways and Transportation (2001) stated that *'To be effective the designer must understand the environment from a pedestrians perspective. A desktop exercise is unlikely to result in a satisfactory outcome for those on foot'*. In principle, this is also true for motor traffic and cyclists. Visiting places provides an insight into how they are used and how they can be improved. However, it is of course not possible to obtain reliable and frequent data from all locations necessary for urban scale modelling. This is particularly true when studying cycle flow, due to the more freely available route choices available when compared to vehicular movement, which is limited to roads.

The major increase in computing power in recent times has expanded the scale and detail of analysis that can be modelled (Hensher and Button, 2008). However, it is the human ability to code, input, run and interpret the data that can create problems with data processing (Ortuzar and Willumsen, 2011). Geographic Information Systems (GIS) lend themselves well to transport modelling as they provide a visual mechanism for displaying results, data management, data analysis and data presentation. GIS can manage large volumes of spatially and temporally disaggregate data used in transport models. The visualisation tools of GIS enable editing, display results, and allow data to be interpreted and used effectively (Dueker and Peng, 2008). Models that require minimal sets of information, that can be run and modified relatively quickly, and that can provide a number of different scenarios based of a range of future situations are favourable with practitioners. Training costs can be high so using an existing model or software package can be advantageous (Ortuzar and Willumsen, 2008). When a model is accepted into everyday working practice by different stakeholders, the process of utilising it can assist with consistent and appropriate monitoring and encourage joined up thinking between stakeholders (Jones and Patterson, 2007).

Robust accessibility models require human behaviour information, which is often in short supply, and both user and trip characteristics at suitable levels of aggregation together with preferences for facilities (Iacono et al., 2010). The number of sampling points needs to be carefully considered together with the frequency of collection, how information will be collated, who will use the data, and whether it can be shared with others. Errors in data will create errors in the model which are more serious for the accuracy of the model than they are in the data (Stopher, 2008). Wells et al. (2007) confirmed that accessibility measurements do not account for cycle routes away from the road network which improve accessibility, or consider physical and psychological barriers to movement which reduce accessibility. In a study undertaken in a shopping centre (Wells et al., 2007), it was found that crow fly distance measurements significantly overestimated accessibility, and that using the road network underestimated accessibility. A study by Lee and Moudon (2008) used GIS to assess the availability of, and distance to, individual utilitarian and recreational destinations. They also measured transport infrastructure including connectivity and block size, pavements, bike lanes and motor traffic volumes together with land use characteristics and topography. Environmental barriers to cycling included too much motor traffic, no bike lanes or trails, nowhere safe to cycle, badly maintained pathways and large distances (Lee and Moudon, 2008). This work supports the development of a model that includes all available routes to cyclists, particularly if based at an urban scale.

Measurement of accessibility is usually concerned with actual rather than potential levels and research into these areas is very limited (Tolley and Turton, 1995). It is assumed that movement is a process which seeks to minimise journey length, time and cost. The quest for route efficiency has been pursued by geographers in the context of route networks where investigations vary between looking at complete inter-linkage to a simpler route. When considering modes of transport, fuel cost is an issue, however, when comparing the choice of

route when utilising cycling or walking, where there is no additional economic fuel cost, an extended journey will not cost any more (Tolley and Turton, 1995). Stener et al. (2009) confirmed that few studies consider the impact of directness or travel time to destination despite evidence demonstrating that this is an important factor for commuting.

2.11 Modelling relative motor traffic flow at an urban scale

Traffic demand is based around space and time, therefore the supply of infrastructure and services need to be represented in a formal way in order to model them at a network scale (Willumsen, 2008). Traffic analysis tools can be used to help improve the decision making process, evaluate alternatives, improve design and evaluation time and costs, reduce disruption, manage capacity, monitor performance and present data to stakeholders (US Department of Transportation, 2004). Potentially useful approaches for modelling motor traffic flow at an urban scale are considered to identify the most appropriate for the needs of the study which include requiring relatively little data but can present information in a clear visual form, preferably using a common GIS package.

Traffic demand models collate as much variation of the types of travel, transport modes available, types and density of populations and how this will all change over time (Bates, 2008). The traditional 'Four Stage Model' (Hensher and Button, 2008) was designed for large scale road construction projects. It is used to look at accessibility between zones and is defined at a regional or sub-regional scale (McNally, 2008). The four stages are:

- 1) *Trip generation* - predict the number of trips likely to enter and leave a zone for different time periods;
- 2) *Trip distribution* - reproduces a matrix of person movements from origin to destination for different time periods and the number of trips that are likely to occur;

- 3) *Modal split* - predict the proportion of persons using public transport or other modes;
- 4) *Traffic assignment /route choice models* – take a matrix of trips and assign them onto the network based on shortest path algorithms.

Different levels of detail are possible within a four stage model and the level of detail incorporated determines the complexity of the investigation undertaken regarding the location of infrastructure in terms of accessibility between different zones. However, the model is cumbersome to operate requiring extensive data collection, model estimation and forecasting exercises which may take years to collate (McNally, 2008; Kitamura et al, 2000; Dickey, 1983). This is not a major concern for long term, large scale investments; however, for smaller scale infrastructure changes the use of such a model may not be economically viable (Bates, 2008). Other issues that exist with traditional four-stage model include:

- (i) traffic flow estimation is typically limited to classified roads, fully representing local road networks requires high levels of detail and coding;
- (ii) walking and cycling have frequently not been included;
- (iii) route choice is only the fourth step of the process (McNally and Rindt, 2008). Also the process is iterative, and that once ‘costs’ from route choice are obtained these are fed back to stage 2 – trip distribution.

Willumsen (2008) stated that limitations exist with trip assignment models as not all links are modelled, trip ends are aggregated into zones, and intrazonal trips are ignored. Therefore, for urban scale evaluation, this type of tool is not appropriate. To make a quick assessment of the potential impact of network changes, requiring minimal data and therefore financial and time investment, alternative models are required.

Sketch plan tools and macroscopic simulation models can be used to provide estimates of traffic operations in response to changes, allowing specific projects to be considered without in-depth evaluation. They are simple to use and less costly, use aggregated data and simplified analysis techniques, but are limited in scope, analytical robustness and presentation capabilities (US Department of Transportation, 2004). Macroscopic models investigate deterministic relationships between flow, speed and density of traffic taking place at a network scale (US Department of Transportation, 2004). They demand less data than microscopic models which analyse section-by-section changes but cannot analyse improvements in great detail.

The *SATURN* (Simulation and Assignment of Traffic to Urban Road Networks) traffic model enables analysis of traffic management schemes on localised networks (Atkins and ITS, 2013; Van Vliet, 1982). SATURN was developed in the early 1980s by the Institute for Transport Studies at the University of Leeds and has developed into a suite of flexible network analysis programs which can be used to investigate road investment schemes from individual junctions and localised networks through to a traffic assignment model for larger networks. The macroscopic model within SATURN allows data such as traffic flow direction, vehicle flows, number of lanes and hierarchical classifications to be included (Atkins and ITS, 2013). This presents a relatively detailed representation of the urban road network (up to 6,000 links) requiring a modest level of data. Two types of network are used in SATURN – (i) the simulation network which focuses on intersections and is applicable to small network applications, and (ii) the buffer network, which emphasizes links and is therefore applicable to wider areas (Barros, da Silva and de Holanda, 2007). However, the data required is very detailed and clear visual outputs are limited which are beneficial for simple, visual assessment.

Space syntax was developed by Hillier and Hanson (1984) in the UK and is now used internationally. Space syntax modelling techniques are based on a configurational axial map of a space, which indicates how spaces are located in relation to each other and can be used to analyse potential performance of a whole urban network (Marcus, 2000). Axial lines represent nodes, with the connections between the nodes creating a graph of spatial components (Hillier and Hanson, 1984). Hillier and Hanson (1984) describe the similarities of urban space to ‘stringiness’ and ‘beadiness’ with strings representing the nodes and beads the connections. This is an easily understood concept for human researchers but is more complex computationally (Turner, Penn and Hillier, 2005). Each axial line, which represents the line of sight within a space, is assigned an integration value which represents attractiveness (Cahill and Garrick, 2008). The axial map can be used to ‘identify routes that are potentially more likely to be travelled’ with integration values being controlled by permeability of spaces and barriers (Pereira, 2012).

One of the strengths of space syntax is that it is based on the ability to *represent* distance between origin and destination rather than simply use the euclidean distance between two points (Kwan, 2000). Distance is not accurately measured within space syntax but all roads are represented within the axial map and therefore are taken into consideration when considering moving from one space to another. Space Syntax relies on accessibility of space measured by ‘calculating the shortest journey between each link (or a space) and all other spaces within the network (shortest being the need to make fewest changes in direction)’ (Hillier, 1998). Space syntax also allows for all links to be included within analysis and for each trip to be allocated to a specific link. As links are not aggregated into zones, all trips are illustrated on the axial map. Space syntax techniques can therefore be used to measure the degree to which each road/path on a map is linked to all other road/paths within the defined system, based on the assumption that routes that are more

integrated will be used more often, whether it is by pedestrians, cyclists or motor traffic. These techniques have the potential to be adapted and enhanced to predict accessibility for other modes of transport and for accessibility to amenities.

Traditionally axial maps have been applied to analyse the effect of the configuration of space on a broad range of architectural and planning applications. For example, following a need to improve the public realm within Trafalgar Square, space syntax was used to analyse pedestrian movements which was supported by an observation study. Problems throughout the masterplan area were identified and solutions, supported by a strong technical argument based on space syntax, were provided, accepted and implemented, which has resulted in pedestrian movement increasing by thirteen times (Space Syntax, 2013). A further application has been to ensure that Kings Cross, an area of 1.5km², was integrated with existing pedestrian patterns whilst linking it with new routes. Space syntax analysis indicated that areas at the edge of the site created segregation therefore reducing pedestrian movement, and a series of mitigating measures could be identified (Space Syntax, 2013). Croxford et al. (1996) indicated that methodologies for space syntax should be applied to a greater variety of urban areas with differing configurations. Ståhle et al. (2007) agree that space syntax linked with geographical data could be of great use in urban planning as it provides the opportunity to incorporate the experimental dimension rather than abstract system-descriptions from traditional transport modelling. Pereira et al. (2012) suggested that space syntax could be used to evaluate different urban configurations on the performance of urban transportation such as travel time.

The ability of the space syntax model to make accurate pedestrian, cycle or motor traffic flow predictions is based on the correlation between the integration values calculated by the model for each link and the flow figures from the spaces (Pereira, 2012). Investigations undertaken

to confirm the predictability of integration values have taken place for different scales of spaces and for different modes of transport. For example, Hillier et al. (1993) investigated the correlation of pedestrian movement in London with axial maps and found strong correlations between integration and movement rates with R^2 value from 0.66 to 0.824 for sub-area analysis. Correlations in this study were particularly strong when logarithmic movement figures were used. Hillier et al (1993) believed that attractors, such as shops, transformed the basic linear relationship to logarithmic relationship as shops act as a multiplier at the pedestrian scale. Pereira et al (2012) reported on work by Cybis et al (1996) where traditional motor traffic model data from AX-I-MAGIC was compared to space syntax integration values for a neighbourhood of Brazil. Pereira reported that only a visual comparison of the results were mapped but it was found that very different results between the two models were found. Work by Barros, Silva and Holanda (2007) also reported by Pereira et al (2012) compared vehicle count data and integration values, with Pearson correlation coefficient of 0.53 which indicated a high degree of predictability between the two on an urban scale, however sampling points within this study were limited. Pereira et al. (2012) own research collected data from 20 data points in Brasilia with results indicating that it is global configurational characteristics rather than local characteristics that are important at an urban scale. Therefore, despite a number of attempts, strong evidence to correlate urban scale data and motor traffic flow is still lacking.

To support the validation of space syntax, Barros et al. (2007) made a qualitative visual comparative analysis of results from space syntax and SATURN for small urban areas. Results illustrate that all streets in space syntax have data ascribed to them when compared to SATURN, which however lacks data on local roads that is, conversely, contained in space syntax. They made comparisons between actual flow figures from a limited amount of speed control devices (31 locations – arterial and collector streets only, not local streets) and space

syntax results and found that there was a good association between actual flow values and space syntax (R^2 0.3/Pearson's R 0.529). Correlations between SATURN and motor traffic flow data were higher, with Pearson's R equal to 0.776. The authors report that for localised roads where no counts were available, results fluctuate, whilst roads with data remain unchanged. They support the use of the space syntax model in that not a large amount of data is required compared to other transport models, and that R^2 values encourage the application of configurational models for traffic studies even if at the initial planning stage (Barros, da Silva and Holanda, 2007).

Pereira et al. (2012) have highlighted that configuration analysis fails to take into account street features that influence urban transportation performance such as road width, pavement quality and traffic lights. Certain features of the surrounding environment are important to map (Turner, 2007) but these are determined by the objectives of the model, the degree of accuracy required and the data available at such a scale.

The *Place Syntax Tool* (PST) has been developed to attempt to incorporate 'attractions' within space syntax (Stähle, 2012). It is believed the combination of space syntax and urban morphology can assist with urban planning and design and therefore Place Syntax has been developed to 'load' geographical data onto predicted movements within space syntax. This tool has been used for pedestrian analysis only to date, but the authors have suggested that it could be useful for urban planning and design practice based on people's needs rather than bureaucracy involved in planning (Stähle, 2012).

Porta, Crucitti and Latora (2006) have developed *multiple centrality assessment* (MCA) to try to understand places that hold greater potential to become the 'backbone' of a neighbourhood or city (Porta and Latora, 2007). MCA can be applied to different spatial systems and at

different scales using substantially different procedures (Porta and Lators, 2007). MCA was developed partly in response to the concept of space syntax. Where space syntax is based on places being more important than others because they are more central or integrated, MCA attempts to go beyond proximity to consider how people experience and navigate systems, and computes the metrics of distances within networks. Conventional space syntax is described as indirect or 'dual' as the streets are nodes and intersections are edges (steps) whereas the MCA approach considers distance in spatial terms, which is considered 'primal'. The ability to incorporate metrics into the model is appropriate for active transport as participants are more sensitive to short distances (Sheurer and Porta, 2006).

Porta, Crucitti and Latora (2006) investigated four 1-square-mile urban street systems using MCA. This research has indicated that the primal approach is more comprehensive for network analysis and that the primal approach is suitable for making the best use of huge information resources developed within cities. They demonstrate that centrality is not the only component within spatial systems and that four concepts of being central come into play: nearness, betweenness, being straight to and being critical to others. Each of these factors relate to a different aspect of a specific location in relation to the rest of the network. MCA involves the creation of a spatial system, represented by a graph which is defined by nodes and links/edges. The edge is defined by two end-nodes and follows the geographical footprint of streets as they are represented on a map (Porta et al., 2008). Each of the concepts of centrality can be considered depending on what the notion of being central is to the study.

Porta et al. (2008) have demonstrated the use of the MCA model to consider accessibility and revitalisation of a University campus in Milan. Two alternative solutions have been tested using MCA to attempt to revitalise the system and the solution to provide a spine shaped cycle/pedestrian route connecting central spaces has been specified as a result of application

of the MCA. MCA has also been used to investigate centrality and best location for active streets within masterplanning activities (Porta, 2013). MCA was applied to the masterplan of Aldershot, to investigate the new large scale mixed use development and is used to identify streets within the development that could add to the social hub of the development. The MCA model has been used by Jones et al., 2012 to investigate the relationship between centrality in the entire street network and frequency of walking and cycling. MCA was used to generate a set of measures based on topographical properties (relation of each node to each other node) and spatial properties (distance between the nodes). Betweenness, closeness and straightness were used. The average and sum of values within each network for each respondents home were calculated. Use of the centrality maps have indicated that most central locations along the entire street network are main strategic arterial roads. This research concluded that connectivity of the street network and availability of everyday activities within a walking/cycling distance from home are insufficient on their own to encourage cycling. This work suggests that they are not the dominant factor that shapes everyday travel decisions.

It is clear that there are advantages of MCA over space syntax, particularly in that metric distances can be calculated within the analysis and different indicators of centrality can be represented. However, the model to date has only had limited application, mainly by the original developers at Strathclyde University and validation of the model has not been documented. Porta and Latoro (2007) confirm that substantially different procedures for different functions increase the level of complexity of the model.

2.12 Modelling cycle flow at an urban scale

Urban spaces are very different from the perspective of a cyclist and car driver. Non-motorised forms of transport, such as walking and cycling, have access to a broader range of spaces

which need to be mapped in addition to the motor traffic based road network (Turner, Penn and Hillier, 1998). There is a distinct lack of evidence based understanding of cycling activity patterns (Law, Sakr and Martinez, 2013) and it is difficult to monitor, model and predict the movement of cyclists at a local level as:

- the number of cyclists is relatively small;
- a wide choice of routes are available therefore the number of locations that need to be measured to obtain reliable figures is dispersed;
- route choice is influenced by human preference more than by car and is planned as a result of attractors and detractors on route.

There is a lack of monitoring data available to validate cycle flow modelling. Key UK guidance document for monitoring cycling was produced 15 years ago (DfT, 1999) and provides the following key methods for monitoring local cycle use which includes:

- Automatic traffic counters (ATCs) – which can be used on major cycle routes which should be validated every six months with manual classified counts. These tend to be unreliable and figures on cycling cannot easily be compared over time at a city level due to relatively small numbers available (Golbuff and Aldred, 2011);
- Manual classified counts (MCCs) – the high cost of hiring enumerators prevents this being the only method of cycle monitoring;
- Cordon and screenline counts – these are used to measure general traffic flow and should include bicycles as an individual category;
- Destination surveys – counting parked cycles at selected locations;
- Interview surveys – roadside interviews are costly but provide an accurate measure of cycle flow data.

Cycling England (2011) recommend that cycling data is recorded before and after the introduction of new measures to help to justify expenditure and demonstrate value for further

investment. Complexities of monitoring are highlighted and included timing and locations of counts and the inclusion of costly automatic counters into scheme budgets (Cycling England, 2011). Transport Scotland (2013) recognised the complexity of collecting data on cycling and identified a number of high level indicators that can provide information about cyclists including the Scottish Household Survey which is considered the most robust source of data on cycling trends in Scotland (Transport Scotland, 2013). These documents provide national statistics only and do not provide guidance for local monitoring specifically.

The UK Government provide guidance on estimating and reporting on active transport through the DfT Transport Analysis Guidance (TAG) Unit. Within the document Active Mode Appraisal (DfT, 2014a) guidance is provided on how to estimate and report impacts on active modes including estimating future demand for transport facilities. Three possible approaches to forecasting demand for new active transport facilities are provided. These include:

- Comparative studies – where future levels of active transport are estimated by making comparisons with similar schemes. This is considered to be the least complex and costly approach. However, contextual factors, such as socio-economics and existing transport facilities vary significantly between schemes and therefore this approach can only provide an indication of potential change.
- Estimating from disaggregate mode choice models – provides a link to a range of bespoke and other mode choice models. These vary according to the population group and the destination, for example the proportion of cyclists who cycle to work on short distances. The results should be regarded as very approximate in general applications due to the limitations of population groups and modes and transferability between modes, particularly to walking is limited.
- Sketch plan methods – Nationally available data sets are presented as providing changes to levels of active transport. These include census data included within the Department

for Transport's National Trip End Model (NTEM) (DfT, 2014b). This provides a useful set of background data that can be used to estimate change for all population groups. However, contextual variations exist between places, over time and for different population groups.

Each of the approaches summarised above can provide a general overview of the potential change associated with proposed schemes. Limitations are associated with each approach mainly associated with generic data requirements and variations associated with the specific location, population group and contextual transport situation.

A general lack of attention to the appraisal of cycle facilities means that most cycle investment decisions are rarely based on empirical evidence, and that more quantitative work would allow a more rigorous evaluation of cycle investment schemes (Law, Sakr and Martinez, 2013; Cahill and Garrick, 2008; Hopkinson et al, 1996). Understanding the key factors behind generation of demand for travel becomes increasingly important when planning future accessibility and mobility. Hopkinson et al (1996) found that investment in new routes, when existing demand is clearly understood, can be beneficial in an economic sense even in unfavourable circumstances. Iacono et al. (2010) stated that there is little execution of accessibility modelling for walking and cycling and where they do exist they tend to be location specific, lack reliable data and computational power and lack of knowledge of non-motorised travel behaviour has prevented progress, particularly at an urban scale. Law et al. (2013) confirmed that there is a need to provide quantitative evidence of the most effective measures between providing legible direct routes or safer but less direct segregated routes.

Work carried out by Allott and Lomax Consulting Engineers for the DfT in 1995 compared conventional desktop and field study investigations with the use of a Dutch cycle traffic modelling package, QUOVADIS-BIKE (QVB) for Ipswich, UK. This trip distribution model

is similar to the four-stage transport model, and as such requires significant levels of data and skill to implement (Cahill and Garrick, 2008). Investigations in Ipswich were carried out to replicate observed patterns of cycling rather than estimate potential demand. Both approaches identified that the cycle network converged onto the town centre and that routes identified as part of the cycle network were commonly identified. However, due to the QVB model being developed in The Netherlands predictions of cycle flows were much higher than could be expected with modal share at 30% compared to existing levels of 6% within the test city of Ipswich. Some modifications were made to the model to rectify this problem although the changes were not realistic and were simply made to ‘improve’ the figures. A further model MVCycle used route assignment methods to predict peak bicycle volumes, which required individual trips to be modelled. Cahill and Garrick (2008) confirmed that the number of steps required to undertake this modelling was complicated and required very demanding skills and data sets which do not support the objectives of the research within this study. Neither QUOVADIS-BIKE or MVCycle allow discrete cycle route choices to be identified.

With regards to modelling cycling and street connectivity, Berrigan et al. (2010) investigated active transport (cycling and walking) based on buffer zones (0.5km radius from the respondents household). They considered variables to analyse street connectivity which included characteristics such as:

- link/node ratio – with links referring to street segments and nodes representing intersections and dead ends. A higher ratio of links to nodes refers to a higher connectivity; and
- average block length – average length of the links are wholly or partially within the buffer, where a higher average length results in less connectivity.

They found that two dominant features: (i) shorter, more connected blocks and (ii) longer blocks with a grid like pattern, were sufficient measures of street connectivity, preserving 84%

of the variation of the data. This is particularly relevant as the data collation and computational requirements to analyse nine variables initially considered, as opposed to two independent sets of data, is much reduced. Although this type of model can be used when point sources are identified specifically, it is not applicable for a city or region wide study where movement from all spaces to all other spaces is the key requirement. It is also subject to personal interpretation as a number of geographical features could vary as result of the complexity of the study. Research by Read (1999) correlated data from axial maps prepared for accessible spaces with walking and cycling data, excluding inaccessible routes such as motorways. Count locations were limited, however, 27 of the 36 areas surveyed scored a correlation co-efficient of over 0.7. A network design model presented by Li and Yu (2013) to model bikeway network design has been applied to a district of Taipei City, China to develop alternative cycleway options for scenario analysis. The model creators have indicated that the model is suited to areas of approximately 10km² rather than an entire urban area due to the amount of data required to populate the model. The authors have attempted to incorporate data on the built environment, transportation needs and connectivity of the network into the model and it therefore incorporated information on a broad range of factors such as population around trip end, cost data for bikeway construction, and maintenance and road slope and width among many others. This type of model would be more appropriate to a particular regeneration programme for a specific urban area rather than at the holistic, regional scale.

Law et al. (2013) have investigated the impact on infrastructure changes on cyclist movement patterns in London using space syntax and have considered a series of perceived safety measures which include the position of routes within the London Cycle Network or the London Superhighway network, level of cycling landscape provision, and the number of vehicle lanes per segment. The first three measures are given a score of 0 or 1 where present or not. However, with the number of vehicular lanes, a discrete variable is given from 0 – 8

based on the number of lanes in both directions. The classifications provided during this study are contextually based in London and are therefore non-transferable to other UK cities. The classification of lanes is also considered subjective and temporal, as this could vary over different times of the day depending on the number of parked cars. A further measure identified to have an influence over cycling route choice within this study is the nature of the land use, where a positive score 1 is given to areas where retail and active land exist, and 0 for no active land use. Again, this could be considered contextual for London as Westerdijk (1990) identified pleasantness as being a key attribute for cyclists, which may not necessarily be associated with retail/active land.

Raford et al. (2007) utilised space syntax to forecast cyclist volumes and route choice looking at the role of urban form and street network design in London. The study investigated commuting trips and used space syntax to analyse the relationship between street accessibility and cyclist route choice. This study undertook comparative route choice compared with actual data and looked at the angular difference between street segments to analyse the impact of topological depth along curved streets. It looked at an area of 120km² which composed of approximately 12,000 axial lines. The study compared the actual route with shortest route and most integrated route (n=46). It was found that 54% of cyclist trace length fell off the ideal shortest or fastest route providing evidence that alternative logics or unpredictable elements such as scenic preference may influence route choice, but this was not analysed further. Research concluded that at the individual level, any number of factors may influence a given cyclist's choice of route such as heavy motor traffic, which were not analysed. When cyclist journeys are aggregated independently of origin and destination, the sum of all interacting routes conform to a powerful spatial logic and that total cycle volume is strongly influenced by configurational variables. Results indicated that although geographic trip length is important, angular minimisation is of equal or greater importance which should be considered

within urban planning and transport engineering. The paper suggested that it could be misleading to analyse individual route choice preferences alone and that analysis of cyclist behaviour should be undertaken at a system level, independent of origin and destination studies (Raford et al., 2007).

Work undertaken by Raford et al. (2005) and Law et al. (2013) identified that correlations between integration and cycling flow exist but confirm that limited data were available and in some locations no cyclists were recorded. From the limited results available from Law et al. (2013) it was found that new cyclists preferred the most accessible, most direct and least angular routes. The study also investigated pre and post installation of cycling infrastructure at a particular location in London and found that cyclists preferred to use routes with more cyclist provision but that cyclists would still prefer to use more direct routes rather than an indirect route with cycling provision. Frequent and reliable data collection within other cities is required to support this further as data for both studies was limited.

Further work by Cahill and Garrick (2008) attempted to correlate space syntax measures and bicycle volumes in Cambridge, USA using ArcGIS. Bicycle volume counts were available for sixteen intersections across the city. As count data was available for intersections it would be very difficult to assign data to an axial line as it could travel along either of the two lines intersecting. Therefore an average was calculated based on values for all four entry points to the junction and the data was combined with census data to calculate origin and destination required for the choice measure being used, as described in Section 2.11. This study generated R^2 values of between 0.3 and 0.65, demonstrating that the model performed well. Higher values were obtained where attractors were included such as population density and worker density which were used to represent the place of work as an attractor. Cahill and Garrick (2008) confirmed that data collection methods were likely to be the reason why space syntax

did not have a stronger influence in the model and stated that data collection points were not random, being located on similar and major intersections within the study area. They reinforced the need for further validation, choosing a random selection of count locations and that the counts should take place on the connection rather than on a node, to allow the model to be used for real transportation planning.

Manum and Nordstrom (2013) have made simple, visual comparisons of intended routes for cyclists and space syntax predicted routes in Trondheim, Norway. They found that space syntax predictions correspond very well to intended bicycle routes generally, confirming that spatial analysis can be very useful for '*grasping the bike route potential of a street network*'. Anomalies were associated with intersections which could add additional time onto a journey which was not considered in space syntax calculations. This fully supports the potential to use space syntax methods for initial scoping of possible infrastructure modifications on an urban scale.

2.13 Summary

The literature review provides a summary of the background principles associated with the implementation of low carbon transport within cities including identification of policies that have driven change at different spatial levels together with the role of the development of urban areas including land use patterns and infrastructures. Evidence that changes to the built environment can reduce dependence on the car are provided (Goodman, Sahiqvist and Ogilvie, 2014; Law, Sakr and Martinez, 2013; Titheridge and Hall, 2006) and that policy needs to be strengthened to support this (Wardman, 2007).

With a replenishment rate of just 1% per annum of the current housing stock in the UK (DCLG, 2006) focus on modal shift needs to be placed on existing urban environments rather than newly constructed areas. Cities that have proven to significantly implement modal shift, such as in Edinburgh and Delft, support taking an urban scale approach that provides a more cohesive, joined up network that promotes cycle use where relatively inexpensive facilities have been successfully located. McClintock (2002) suggested that by relying less on special facilities for cyclists and more on reallocation of roads away from motor traffic, cycling journeys could be made shorter creating a more sustainable movement system. This is reiterated by Cahill and Garrick (2008) who indicate that limited funding is available for major infrastructure changes to take place with on-road facilities being the most favourable options. Guidance is required to identify the most appropriate routes to support cyclists in order to achieve the sustainable travel targets that have been set. This should encourage cross sector working to enable investment to have an impact on broader society. By improving connectivity within the built environment and therefore access to key services and the workplace, distances will be reduced and along with this, dependency on the car, which in turn will support an improvement in the economy, society and the environment (Manum and Nordstrom, 2013; Jones, 2012; Lee and Moudon, 2006).

The review of space analysis methods has demonstrated there is considerable potential for predicting motor traffic and pedestrian flow at an urban scale and associated accessibility and connectivity in fine detail, down to street or sub-street level for a large number of roads, whilst having the potential to represent all roads/routes of access within a large urban or regional area. The review indicates that the space syntax approach would be suitable for investigating the potential to model motor traffic and cycle flow at an urban scale to identify routes within a city that can be targeted to improve accessibility for cyclists.

Chapter 3: Methodology

3.1 Introduction

This chapter provides an overview of the modelling approach taken and is split into sections which are summarised below:

- description of the development of spatial analysis model;
- overview of the principles of spatial analysis modelling procedure;
- justification and description of case study cities and regions to be used for the validation and testing.

Detailed descriptions of the analytical processes applied to validate and demonstrate the modelling approach are then provided as below:

- Chapter 4 and 5 - validation of an aggregate urban scale motor traffic flow spatial analysis model;
- Chapter 6 and 7 - demonstration of the application of the spatial analysis model for aggregate relative cyclist flow and investigation of infrastructure change on cyclists and motor traffic flow;
- Chapter 8 and 9 - analysis of individual cyclist movement using the spatial analysis model and cyclist behavioural data from a questionnaire.

Figure 17 presents the interactions between the processes involved with data collection for the three main stages of the research work together with the data requirements and expected outputs. In addition to the data generated specifically through the completion of the research described in this thesis, background data from external sources has been utilised. This includes a large amount of data required to undertake the validation work together with information about travel behaviour and geographical information. These data sources are referenced throughout.

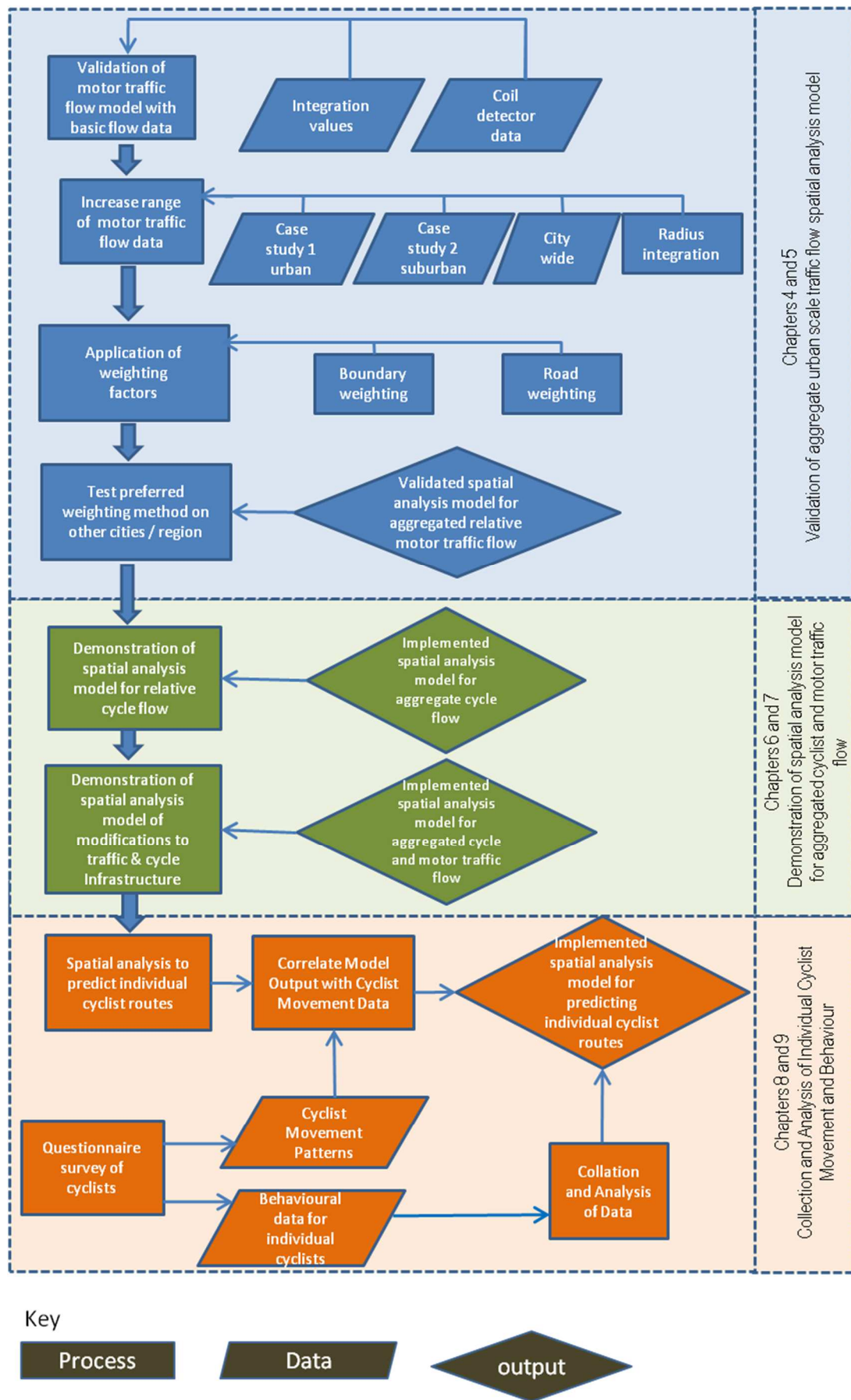


Figure 17 - Illustration of the processes, data collection and expected outputs

3.2 Description and justification of modelling procedures

3.2.1 Background to spatial analysis model development

Following a review of potential spatial analysis software, space syntax has been selected, applied and validated to predict motor traffic flow and investigate the potential to model cycle movements at an urban scale. The space syntax modelling technique used was novel in that it is based within the commonly used Geographical Information System (GIS) desktop software, MapInfo version 12.0, published by MapInfo Corporation, the first time space syntax was applied in this software.

The motor traffic flow modelling work was initially developed at the Welsh School of Architecture as part of the establishment and development of the Energy and Environmental Prediction (EEP) model through funding from the EPSRC (project codes GR/L81536 and GR/K19181) and this work included the development of space syntax techniques based in MapInfo. Additional funding from the Department for Transport LINK FIT (Future Integrated Transport) Programme has also been utilised (ref: STP 14/6/15).

The EEP model was initially developed in order to help manage the use of energy by the built environment in a more sustainable way, and to minimise CO₂ (and other) emissions at a city wide or regional scale (Jones, Patterson and Lannon, 2007). The model (EEP) was developed in collaboration with local authorities in South Wales, UK, as part of a unified effort to plan for sustainability and to predict and account for reductions in CO₂ and other emissions from different sectors of the built environment (Jones, Williams and Lannon, 2000). The computer model provides information to implement urban energy management and environmental

planning strategies, enabling decision makers to plan for improved energy efficiency and to improve long term, consistent data collection to help achieve targets.

The model was developed so that it can be transferred to other cities to predict the effects of future planning decisions from a whole city level down to a more local level. Initially developed using data from Cardiff and Neath Port Talbot County Borough Council (NPTCB), EEP has been used in other local authorities in the UK and Australia (Jones et al., 1999). It has been developed to include housing energy, non-domestic energy, industrial energy use, dispersal of air pollution and health aspects including mould growth in the home, respiratory disease, accidents and injuries in the home (Lyons et al., 2006) and neighbourhood quality and mental health (Thomas et al., 2007).

MapInfo was chosen as the primary user interface for the EEP model because:

- data is stored and manipulated within a database which is relatively easy to use;
- it is capable of storing data for all roads on a city or regional scale;
- output can be displayed as a spreadsheet or in map form enabling clear visualisation of results which is important for sharing data between users of varying skills and experience;
- it is familiar to many local authorities in the UK who are the main potential users of the model;
- it is relatively cheap to purchase and can be used on any PC of standard specification.

The author of this thesis has been involved in the development and application of the EEP model, in particular its application in South Wales to model housing energy, motor traffic flow and health. Whilst the development of the various sub-models which make up EEP has been a collaborative effort over many years, the research presented in this thesis focuses on the

validation of the model for motor traffic flow, and the demonstration of how the model could be used to model cycle flow and associated infrastructure, is the work of the author.

The framework for the EEP model is shown in Figure 18. The model is accessed via a 'primary user interface', which takes the user through a decision making process, presenting information and options and the opportunity to enter data in a straight forward manner.

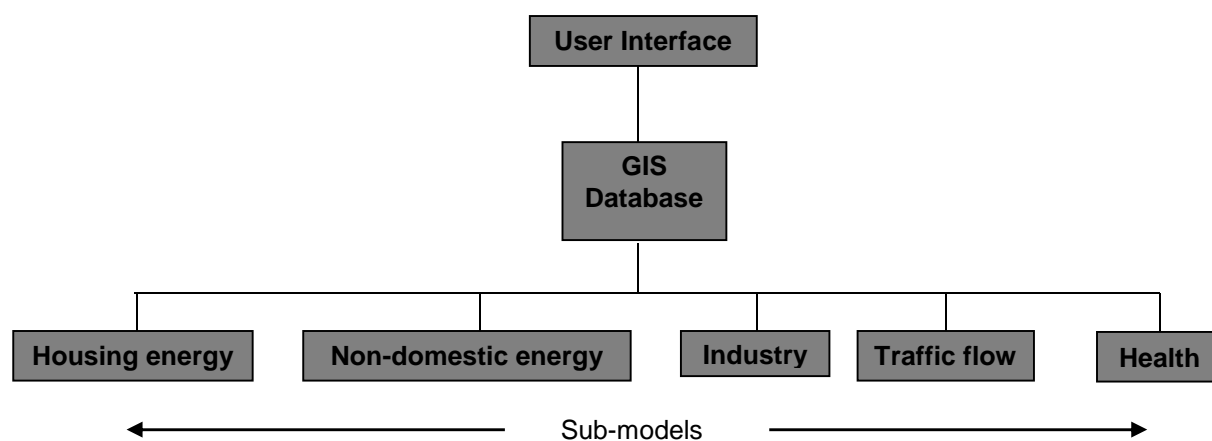


Figure 18 - Principal Components of the EEP Model Framework, including sub-models

The interface has access to a range of external procedures or sub-models, selected according to the user's needs, for example, to predict the city's energy and emissions from buildings, transport and industry. The EEP model presents results through the associated GIS (i.e. MapInfo) which contains an Ordnance Survey (OS) map of a city describing the buildings and road network. Sub-models exchange data through a 'data highway', making all data available to all sub-models. Data can then be mapped using the GIS facilities, for example identifying houses of high energy use predicted by the energy sub-model in EEP. The spatial analysis procedures described and developed within this thesis are a component of the EEP model.

3.2.2 Overview of the spatial analysis method

Spatial analysis techniques used within the GIS based model are able to represent, quantify and analyse space at different levels. The spatial analysis techniques provide an objective measure of the relative accessibility of every road/path within the geographical area under investigation and can analyse change in flow patterns as a result of fine network changes. The technique used within the model is based on methods developed at University College London (Hillier B and Hanson J, 1984) (described in Section 2.11).

Space syntax is a collective name given to a set of computer based modelling techniques used to objectively represent, quantify and analyse space at all levels of the built environment, from a single building to entire cities. The axial map is a two-dimensional map created by a set of lines drawn along lines of sight which is connected. This map attempts to quantify the configuration of space through the allocation of integration values. Integration values provide a measure the connectivity of each line of sight within the map to all other lines. Turner, Penn and Hillier (2005) present a statement that is the basis for the definition of an axial map ‘An axial map is created using a minimal set of axial lines such that the set taken together fully surveils the system, and that every axial line that may connect two otherwise unconnected lines is included’. Therefore all axial links should be made within the system being investigated. Within this paper they go on to present the algorithmic definition of an axial map which is initially created from an ‘all line’ map of the system which are lines generated from the vertices of buildings and infrastructure which are extended to visible vertices within the space. This map is created by the use of axial lines as nodes and crossing points as connections. All possible connections between lines that are not connected are then made. The map is derived directly from the way vertices on built form features relate to each other through open space. Turner, Penn and Hillier (2005) confirm that it is vital to survey the whole space and

that topological rings should be complete. This thesis accepts the basic concepts of space syntax.

A road/path is represented on GIS MapInfo as a line or series of lines that follow the line of sight along a network - these are called 'axial lines'. Any change in direction or an inaccessible route is represented by a break in the line and/or the creation of a new line. Figure 19 illustrates a small area of a city with the axial lines representing motor traffic access. Point A demonstrates a change in direction due a non-linear route. At location B a route is not accessible for cars and so no link is made between two juxtaposed roads.

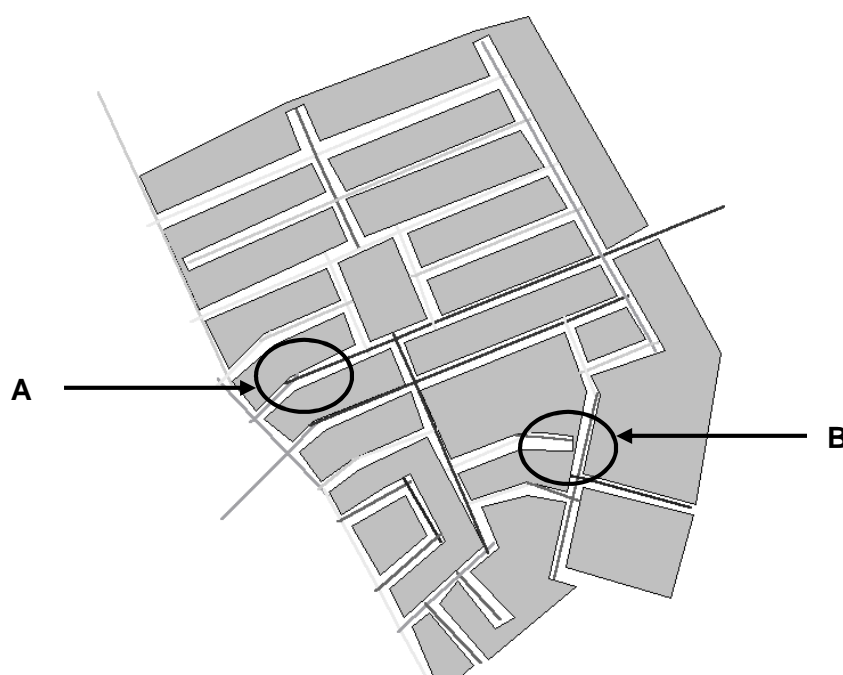


Figure 19 - An axial map demonstrating axial lines for motor traffic

An axial line or road that is easily accessible from all points is described as being well 'integrated', whilst roads that are relatively isolated are 'segregated'. The model algorithms, described in Turner, Penn and Hillier (2005), assume that roads/paths that are well integrated are used more frequently than those that are less integrated. The map is understood by the software to be a set of elements that connect to each other in a combination of sequences. The

software simulates journeys from all potential origins (axial line) to all potential destinations (all other axial lines). The software assumes that a journey will take place on the path that involves the least number of changes of direction between each possible origin and destination. Following this complex set of calculations, a single 'integration value' is calculated by the model for every axial line within the road system taking into account how well linked every route is to all other routes represented within the network i.e. a relative measure of integration. The higher the integration value the better connected the route. An axial line that is well connected within the network under investigation is considered well integrated, whereas one that is poorly connected is segregated. By identifying the integrated structure of a city or regional space the most integrated and segregated routes can be identified. Planning considerations can then be made to improve or otherwise modify the connectivity and therefore accessibility of these areas.

Basic axial map techniques are used within this thesis as they are simple and therefore relatively quick to apply at an urban scale. The simpler the modelling and the data collection process, the more likely it is that the model will be used in practice and will be transferable across disciplines and between staff of different technical competencies. Complexity adds to subjective interpretation and the need for additional data collection. Efforts within this thesis are to minimise data requirements, whilst providing a level of validation that is acceptable.

If successfully validated by comparing predicted results with measured flow data, the model can be used to identify routes that are likely to be used within a city, assuming that those that are well integrated are more connected and will therefore be used more. This will enable transport strategies to focus on routes of high use in order to provide improvements for sustainable modes of transport. This method does not enable flow patterns at specific sites to be accurately modelled (e.g. multi directional motor traffic flow at a specific junction) but

provides a more holistic view of a city or region, providing relative flows based on real count figures and movement.

3.2.3 Creating an axial map

The first step involved in using spatial analysis techniques was to create a network axial map. An axial map for the network under investigation was constructed as a series of lines created as a layer within MapInfo using a digital Ordnance Survey (OS) Landline map or equivalent. This included the existing built environment features such as roads and buildings. An OS digital map, which can be a raster map of an area or a vectorised map such as the Landlinetm and Mastermaptm or other digitally based maps, can be used as a template for the study region if available. Pre-described road-centre line maps have been used for some studies as described below, however, as the axial maps in this study were used for motor traffic and cycle traffic, the axial maps were created by the author.

An axial map is represented by a series of axial lines which follow the line of sight along roads / paths throughout the network. Lines of sight for every single road/path were drawn onto a new layer within GIS MapInfo along all routes that the mode of transport under investigation could travel. The axial map can easily be altered to represent changes in the network and assess new routes as they are planned simply by adding a line into the network. This study involved the production of axial maps for motor traffic and cycle traffic for six case study cities as described in Section 3.3. Digital OS maps were provided by local authority partners for all cities studied.

Axial lines for every road within the network under investigation were manually drawn onto new layers within the GIS MapInfo package for motor traffic and cyclists. The creation of

these maps enabled the assessment of the connectivity of all potential motor traffic and cycle routes within each urban network analysed. Examples of axial maps can be seen in Figure 20. A number of important factors were considered when creating the axial maps:

- it was essential that every line that was drawn crossed the juxtaposed line if there was a junction present in the road system. If the lines did not cross the model would assume that there was no link and integration values would not be true;
- where dead ends were present, the lines were not joined as there was no access point for the mode of transport to pass through;
- at present the model is unable to take account of the one-way system within the network which therefore over-represents reality. It was not possible to modify the model to enable the regulatory environment to be considered within this thesis;
- locations where bridges or tunnels exist resulted in axial lines crossing on the map although in reality the network at these points were not connected. Therefore, an ‘unlink’ facility was incorporated within the model to allow for the distinction to be made where lines may cross on a map but where no actual link exists.



Figure 20 – Examples of axial line maps for different areas of a city (red lines indicate well integrated routes, green indicates less integrated routes)

Axial lines of major routes into case study cities were extended to allow for representation of flow from external areas into the mapped area during the validation process. Once all of the

lines were drawn onto the axial map for the city under investigation, spatial integration values were calculated for every line within the network. These can be colour coded according to integration value, typically red for highly integrated through to blue for less well integrated. The modeller controls the way the data is represented during the production of the map/graph.

Issues that arise during the production and application of the axial map. For example, much debate has taken place regarding the minimum number of axial lines that can be used to represent a space and how these axial lines relate to each other (Penn et al, 1997; Peponis et al., 1998; Turner, Penn and Hillier, 2005). Different methods for creating axial maps have been compared to identify the minimum number of lines required to enable calculations to represent connectivity and integration to a sufficient level of detail and accuracy (Turner, Penn and Hillier, 2005). Figure 21 below demonstrates the variations of techniques and algorithms used for a simple space. Therefore a formulated method for the creation of axial maps to be used across studies is required in order to allow reliable comparisons to be made.

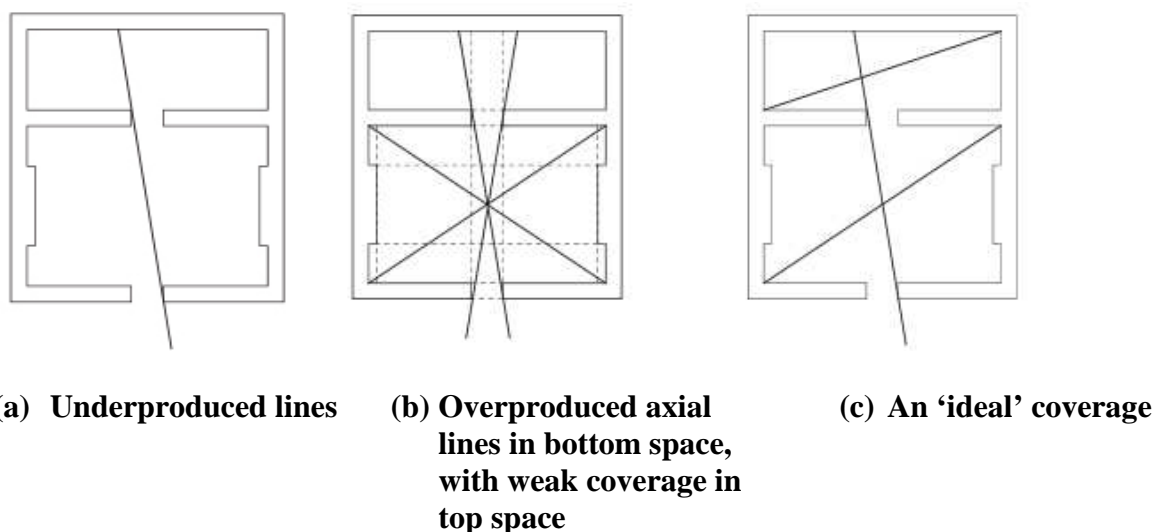


Figure 21 - Axial lines produced from differing algorithms for a simple space (Turner, Penn and Hillier, 2005)

The interpretation of spaces can be subjective. For example, during tests of the hill village of Gassin, Hillier and Hanson used two axial lines to represent a staircase, where in another example of the same space created by another user, one axial line was used (Turner, Penn and Hillier, 1998). On a small scale this can produce different results. Therefore the system used needs to have minimum interference from the personal preference of the modeller (Turner, 2007). It is important to consider the eventual use of the map that is being created (Batty and Rana, 2004). For example, if a map is to be used for the interaction of society with space, then the scale should be based at an individual scale taking into account the features of the landscape with the detail of the road being appropriate (Turner et al, 2001).

Various approaches have been developed in an attempt to represent space differently using space syntax. These are described as follows and where appropriate are applied in Chapter 4:

- Angular segment analysis (Turner, 2004) introduced the incorporation of angles between axial lines. This allows the angle between two axial lines to be weighted creating an ‘angular depth’. A corner of 90° represents one full step, 45° corresponds to 0.5 step, as the corner would be considered easier to manoeuvre. Traditional space syntax does not treat the angle of two lines any differently, just recognising a change in direction, by a break in the axial line. It has been noted by Cahill and Garrick (2008) and Raford et al. (2007) that angles are relevant to cyclists as it is understood to be easier to cycle along a straight route, rather than make sharp turns at intersections. Law et al. (2013) found evidence that faster cyclists do use routes with least angular cost i.e. fewer sharp turns. However, the amount of ‘turn’ that is required to get from an origin and destination should be approximately the same (Turner, 2007), this additional feature may complicate the simplicity of the basic axial map unnecessarily.

- Segment map (Turner, 2004) can be used to assess visual accessibility from one location to inform the choice of next destination. This model works well on small to medium systems but has been described as cumbersome for larger scales (Ratti, 2004)
- Choice measure is where all points in the network are considered origins and destinations and the amount of travel along each line is quantified, representing the extent a particular axial line is part of a shortest route between an origin and destination (Manum and Nordstrom, 2013; Cahill and Garrick, 2008). The most direct path connecting them is identified. When each path crosses a segment, that segment's 'choice' rating increases. The choice measure has been used by Cahill and Garrick (2008) to represent bicycle movement and is discussed in more detail below.
- Road Centre-line varies from a traditional axial map as these are based on Ordnance Survey land-line data (Turner, 2007). Road centre-lines have many slight bends making them very deep, therefore the centre-line map has many more 'segments' than a traditional axial map of the same space. The same road within an axial map may only have one line along the line of sight, whereas a road centre-line may have many (Turner, 2007). There are problems that relate to this in that the base map is reliant on an external organisation to create the it (Ordnance Survey), which can result in uncertainties associated with accuracy and limitations on data update (Dalton, 2003) although such an approach can save time for the research team. The road centre-line map is also generated for motor traffic and would therefore not be easily transferable for other modes of transport such as the bicycle.
- Edge effect was introduced by Hillier et al. (1993) who stated that movement patterns within a catchment area must be related to the larger catchment area, the 'Catchment area of the catchment area approach'. This displaces the natural edge effect, where movement includes information from the prime area of interest together with information from the immediate vicinity of the site that may be impacted (Smith and Blewitt, 2010). Turner

(2007) created an axial map of 3km by 3km for a study area of 1km², which illustrates a 9:1 ratio of additional modelling resource for an isolated area. Cahill and Garrick (2008) used a buffer area of 8.05km within their bicycle study in Cambridge, Massachusetts. On a small scale, extending the axial map to contain a catchment area is not that time consuming but when considering larger urban areas of over 100km², the additional resource to represent the edge effect would be large. This is a current limitation of space syntax.

- Radius integration can be used to appraise local integration of axial maps which has been shown to improve levels of correlation between predicted and real flow in some studies for non-motorised transport. For example both Manum and Nordstrom (2013) and Law et al. (2013) have found that higher radius measures correlate better with cycle flows. This method was first demonstrated by Dalton (1997) and Penn et al. (1998) who applied the principle to the modelling of pedestrian movement. Radius integration ‘looks’ at the number of connecting axial lines that are a small number of changes in direction away from the road being investigated and relates the depth of the degree of integration of each axial line. For a ‘radius 3’ analysis, calculations are made to identify the number of axial lines that are 3 or less changes in direction away from each individual road. Axial lines that are more than 3 changes in direction are discarded from the integration calculation for that particular axial line. The more axial lines that are within 3 changes of direction, the more locally integrated the road under investigation is, the higher the integration value and therefore the higher the likely relative motor traffic flow as route is considered to be more locally connected. Radius integration can be used to remove ‘edge effect’ and can be used to investigate local change but does not take into account metric distance which can influence distances if relatively long, straight routes are included within the space investigated (Turner, 2007). This is particularly relevant for non-motorised transport due to the limited distances that are travelled.

3.3 Case study cities and region used for testing

3.3.1 Justification of case study cities/region

Data relating to a range of cities from across the UK were used to test the spatial analysis models within the thesis. Cities develop over time and this is reliant on the complex mix of geographical resources, historical development and social and political characteristics of the area. This leads to a complex and unique distribution of housing, commercial, manufacturing, industrial and transport infrastructure within each city/region. For example, a city with finance, trade and service at its core is likely to have a highly developed, dense central business district (CBD) whereas a city dominated by manufacturing is likely to have a weaker CBD with outlying centres resulting in different concentrations of traffic (Lapin, 1964). As such, all cities and regions have unique traffic and sustainable transport characteristics and requirements. A successful model should be applicable to all cities/regions and therefore these factors could not be used to justify the selection of one city or region over another when validating the modelling approaches taken.

The primary requirement when validating a modelling approach is the availability of real world data to compare and contrast with the simplified output from the model. As such the primary criteria used to select the cities/regions considered in this thesis were:

- 1) whether established associations were in place with local authorities and/or other partners within the localities who were able to provide information required to contribute towards the provision and capture of relevant data;
- 2) whether the data required to undertake the analysis were available within the organisations;

- 3) whether the mechanisms to capture any additional data required for model development/validation could be developed and implemented within a timeframe appropriate for this study.

As a result of the above considerations, the main case study city used was Cardiff, due to the availability of data, good association with staff who provided the necessary information, together with familiarity with the built environment and proximity to the place of research. Cardiff was the main test city for the validation of the motor traffic flow model with favourable methodologies then tested on other cities and regions where data was available and a relationship with local authorities had been established, including Leicester, Leeds and the Neath Port Talbot County Borough (NPTCB) area.

Cardiff, Bristol and York were used as case study cities to investigate the application of the model to urban cycle networks and the behavioural factors that might influence cycling uptake. These cities vary in the development of their existing cycle networks and other factors that may influence the decision whether to cycle, such as traffic congestion and gradient although they all represent medium sized UK cities without extreme geographical environments, therefore allowing for comparison with other similar sized UK cities. These cities were selected as a result of relevant organisations within the cities providing their support and the ability to provide relevant data.

Table 2 includes data regarding the location, climate and demographics of each case study city/region. Whilst not being a quantitative criterion for the selection of case study cities, it is believed that the cities selected represent a cross section of urban and semi-urban environments in the UK. The cities and regions selected are briefly described in the following sub-sections and the locations are illustrated in Figure 22. Ideally the same cities / regions would

have been used in both cities but this was not possible due to data availability and associations with relevant local organisations.

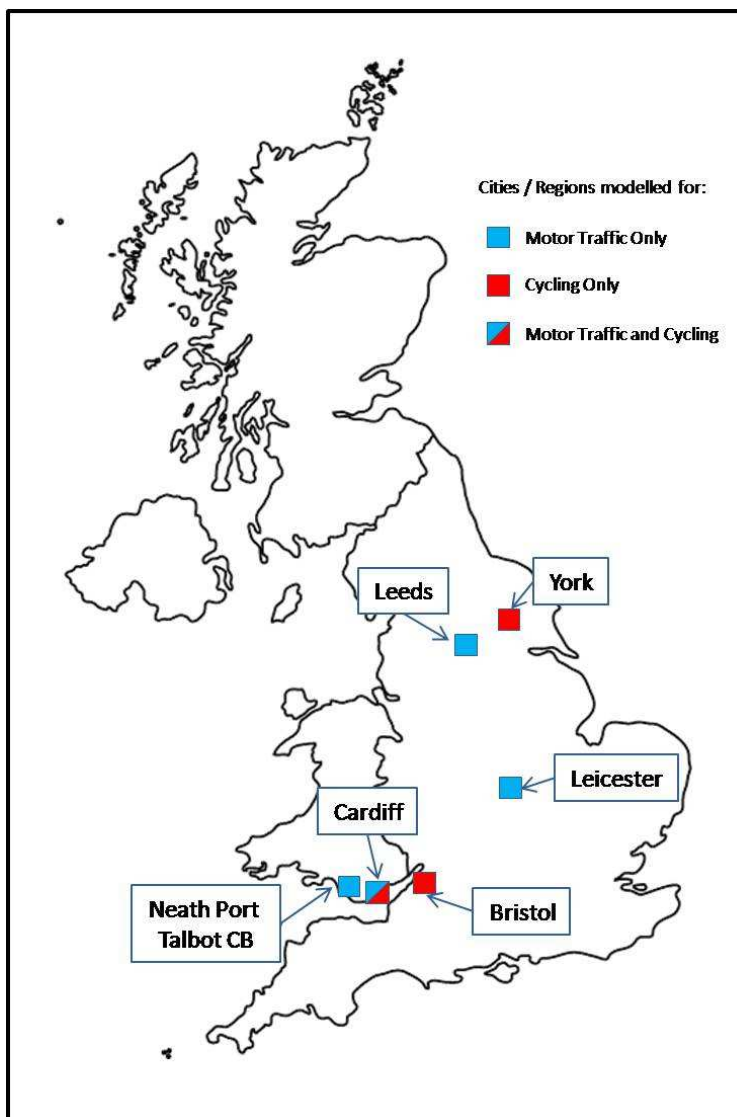


Figure 22 – Location of six case study city/regions in the UK

Table 2 - Comparison of features of case study cities / regions

		Bristol	Cardiff	York	Leeds	Leicester	NPTCB
Location¹	Latitude ° N	51.5°	51.5°	54 °	53.8 °	52.6	51.6 °
	Longitude ° W	2.6 °	3.2 °	1.1 °	1.55 °	1.1 °	3.8 °
	Size km ² (ONS)	109	140	271	551	73	441
Climate² (Met Office, 2011)	Min temp range °C	1.0 – 11.9	2.1 – 12.8	0.3-10.6	1.6-12.4	1.2 – 11.4	2.1 – 12.8
	Max temp range °C	6.6 – 21.2	7.9 – 21.5	5.1 - 19.4	6.4 – 20.8	6.9 – 21.3	7.9 – 21.5
	Days of air frost (annual)	45	33	53	33	48	33.0
	Sunshine (hrs per year)	1,565	1,518	1,398	1,381	1,388	1,518
	Days of rainfall ≥1mm (per yr)	123	146	129	132	113	146
	Av. rainfall per year (mm)	719	1,112	825	825	606	1,112
Population	1991 (ONS)	392,200	296,900	172,300	706,700	281,500	138,800
	2001 (ONS)	390,000	310,100	181,300	715,600	282,800	134,400
	2011 (ONS, 2013a)	428,234	346,090	198,051	751,485	329,839	139,812
	% increase (1991 to 2011)	8.5	14	13	6	15	1
	Density (people per Km ²)(ONS, 2013a)	3,929	2,472	730	1,364	4,518	317
	Households (ONS, 2001)	162,090	123,580	76,920	301,614	111,148	57,609
	Potential workforce	279,083	220,355	134,547	520,479	198,922	96,223
	Size of population of city compared to UK http://www.ukcities.co.uk/populations/	10 th	12 th	31 st	3 rd	15 th	N/A

1 Google.co.uk

2 Climate data for Bristol is from the Lyneham weather station, York data is from High Mowthorpe weather station, Cardiff and NPTCB is from Cardiff weather station, Leeds is from the Sheffield weather station, Leicester is from Sutton Bonington. Source: Met Office, 2011. Data is taken for the period 1971-2000.

Figure 23 illustrates overall CO₂ emissions for the six case study cities/regions (AEA, 2011) demonstrating the variation between geographical areas. Since 2005 emissions have decreased in all areas with reductions in all sectors including domestic, industrial, commercial and road transport sectors (DECC, 2011c). NPTCB had significantly higher CO₂ emissions per capita than any of the other cities. This is attributable to the industrial background, particularly the Port Talbot Steelworks, which is the largest emitter of CO₂ in Wales (National Assembly for Wales, 2009).

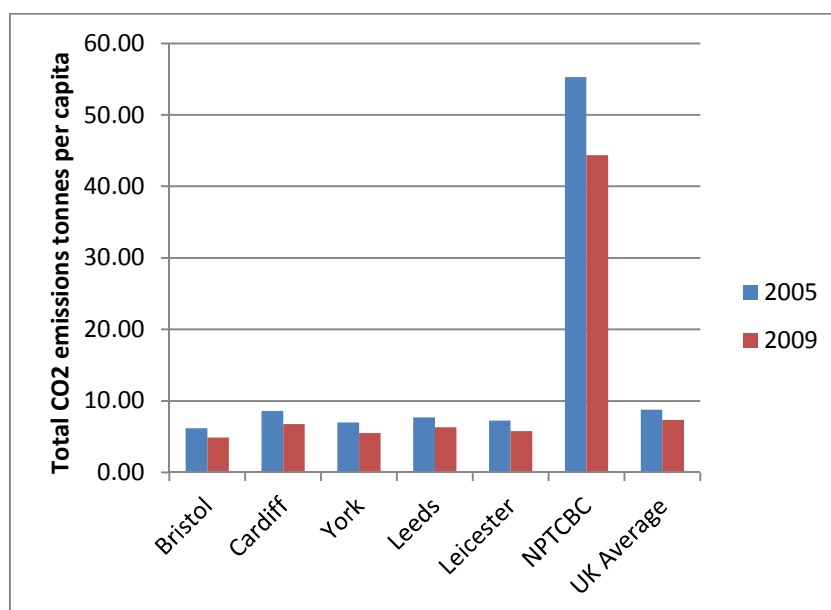


Figure 23 - CO₂ emissions as tonnes per capita for each of the case study / regions for 2005 and 2009 (DECC, 2011c)

When looking at road transport CO₂ emissions per capita, as illustrated in Figure 24, variation between the areas is much less significant. All areas have seen a decrease in emissions between 2005 and 2009.

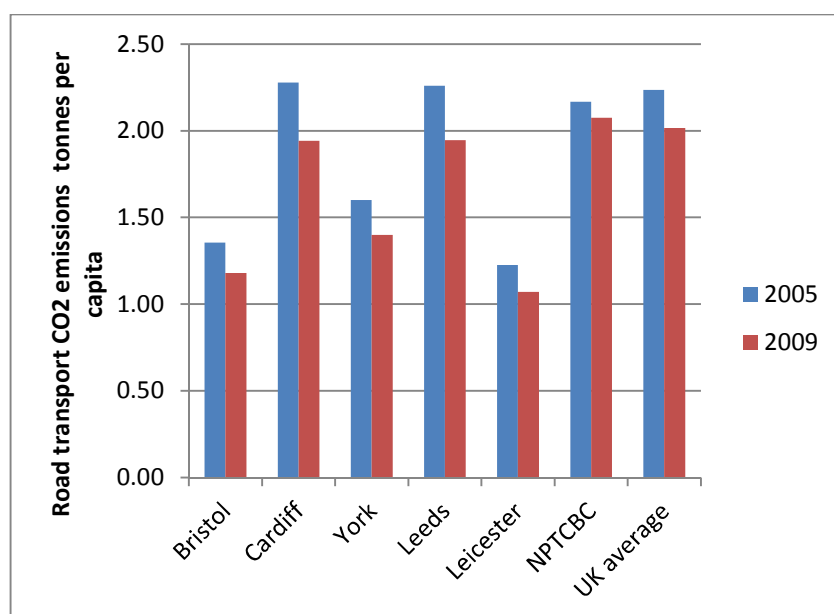


Figure 24 - Road transport CO₂ emissions as tonnes per capita for each of the case study cities / regions for 2005 and 2009 (DECC, 2011c)

3.3.2 Cardiff

Cardiff is the Capital and the largest city within the principality of Wales. It is a relatively flat city with hills to the east, north and west and the coast to the south. Cardiff has a strong industrial heritage which supported the development of the city's rail network. Existing infrastructure in Cardiff is under increasing pressure due to recent growth in population, a 14% increase over 20 years, as illustrated in Table 2 (ONS, 2013). Cardiff has a high influx of commuters and thus has an interdependent relationship with the surrounding region, benefitting from an extended workforce but also generating and sharing affluence and opportunity. This relationship is illustrated by the continued growth in commuter numbers from outside of Cardiff, which increased by 12% (69,000 to 77,000) between 2002 and 2006, with the number of commuters travelling from the adjacent authorities of Rhondda Cynon Taff increasing by 20% and those from Caerphilly by 19% during this period (Cardiff County Council, 2011b).

In March 2009 it was announced that Cardiff was to become Wales' first 'Sustainable Travel City' and that £28.5m would be invested by Cardiff County Council and the Welsh Assembly Government on transport improvements across the city (Cardiff County Council, 2009). A range of projects were designed to help create safe, reliable and sustainable modes of transport bringing environmental, social and economic benefits across the city. For example 'Smarter Choice' measures gave information and encouragement to try a different way to travel for some journeys, and focussed on getting people to plan in advance how they were going to travel. This included car sharing schemes, travel plan initiatives and travel awareness campaigns.

A new cycle network across the city, developed under the 'Enfys' and 'Safe Routes in Communities' schemes, was launched in 2012 (Cardiff County Council, 2011c) focussing on creating improved access to local community facilities and recreational areas within the city to increase uptake of cycling. Cardiff is one of ten local authorities in South East Wales that is part of the South East Wales Transport Alliance (SEWTA) which prepares and co-ordinates regional transport policies, plans and programmes on behalf of the ten councils involved. SEWTA work at a regional scale and prepare regional strategies, apply for funding for those strategies and provide advice to the Councils on strategic, regional and local policy.

3.3.3 Bristol

Bristol is the 10th largest city in the UK (UK Cities, 2013). It is located on the River Avon and has a hilly terrain. It has a strong industrial history due to its proximity to the Bristol Channel and the ports of Avonmouth and Portishead and is itself a historic port. Like many UK cities Bristol experienced huge growth following the Second World War, concentrated in suburbs around the centre. Since the 1980s a significant regeneration programme has been undertaken

which has had a significant influence over the urban form of the city and its environs. Mixed use has been increasing through brownfield development in central areas (Punter, 2009) with a number of Policy documents, including the City Centre Strategy 1998, The Bristol City Centre Strategy and Action Plan 2005-2010 and the Bristol Development Framework Core Strategy 2011, including the promotion of connectivity and accessibility of areas as core themes through mixed use and density.

Bristol was chosen as England's first cycling city in 2008 and received a grant of £11m from the DfT to transform cycling facilities in the city (Better by Bike, 2012). This investment was used to increase on-road cycle lanes, new traffic free routes, new parking spaces and measures such as training and awareness programmes. The Local Sustainable Transport Fund provided by the DfT has allowed the local authorities that cover the Bristol city area to work together to improve links between towns and cities. Bristol is the only UK signatory City of the Charter of Brussels set up in 2009 (European Cycling Federation, 2009) aiming to achieve 15% modal shift by 2020. Bristol has been awarded the European Green Capital for 2015 (Bristol Green Capital Partnership, 2013). Through this initiative the city aims to create local communities that are easily accessible, that reduce the need to travel by polluting vehicles, in which it is safe and pleasant to walk and cycle.

3.3.4 York

York is a historical town including pockets of internationally leading manufacturing companies with outlying centres and is the 31st largest city in the UK (UK Cities, 2013). York took an ambitious early approach in forming a long term cycling strategy following the change in UK policy in the late 1970s and early 1980s. A series of documents have been produced that describe the process of attempting to increase cycling in the city, including the Cycling

Strategies from the Local Authority's Local Transport Plans (City of York Council, 2000; 2006; 2011). The Council has worked with many organisations such as the University of York, the Ministry of Defence and Sustrans who were involved in the initial construction of purpose built cycle paths (City of York Council, 2000). By 2006, 80 km of off road routes, 60 km of on road cycle routes and cycle racks or lockers were installed at all park and ride facilities in the City and 37% of residents considered themselves to be cyclists. The Local Authority reported a change in use of the network with fewer short journeys made between the home and work, and an increase in orbital or cross city trips as a result of changes in land use patterns with a reduction in traditional work places in the city centre and an increase in out of town destinations. Conflict between cyclists and motor traffic was consistently identified by a number of user groups as being a key deterrent to greater cycle use.

In 2008, the City of York Council and Cycling City York submitted a revised cycling strategy for the city to Cycling England. Targets described in the document include an increase in cycling participation of 25% of current (2008) levels by 2010 and to increase cycle trips to work from 12% to 13.2%, among others. Among the aims of the strategy were to provide connections and new routes and to improve the availability and quality of minor infrastructure and to influence travel to work decisions. A survey in 2010 indicated that cycling rates had increased by 10% from 2008 levels, and the Cycling City programme (the Cycling Strategy within the Local Transport Plan 2006-2011) was identified as the primary reason for the increase. The City of York Council (2012) has undertaken a public consultation in order to prioritise locations at which improvements to the cycle network can be made.

3.3.5 Leeds

The City of Leeds is the second largest metropolitan area in the country after London. Since the 1970s the City has seen an increase in the number of commuters as regeneration of historic industrial areas took place, and this trend has accelerated over the past 15 years with an increase in employment associated with the growing financial, legal and retail sectors in the City. The City of Leeds forms part of the West Yorkshire Integrated Transport Region which is the body responsible for defining the regional transport strategy. The West Yorkshire Local Transport Plan 2011-2026 sets the objectives of improving connectivity to aid economic growth across the region and to make substantial progress towards implementing a low carbon transport network in West Yorkshire (WYLTP, 2011).

Historic data for motor traffic entering the inner city perimeter showed rapid increases between 1980-85 (+15.2%) and 1985-90 (+18.4%) with the rate of motor traffic growth then slowing 1990-95 (+4.2%), 1995-2000 (+5.5%), 2000-05 (+4%), before recent reductions in traffic 2005-09 (-2.2%) (Leeds City Council, 2010). This recent reduction is reflected in modal shift figures which show in bound car journeys accounting for 61.2% of journeys in 2000 and 55.2% of journeys by 2009, with significant increases in inbound train journeys (from 9.5 to 17.8%) and more minor increases in walking (from 2.5 to 3.1%) and cycling (from 0.4 to 0.9%) (Leeds City Council, 2010). Sustained, annual reductions in motor traffic are evident from the most recent traffic monitoring report which takes data from a range of road types located on 30 sites (i.e. a different sample from previous survey) and shows a 7% reduction in motor traffic between 2006-2011 (Leeds City Council, 2012a). In September 2012, Leeds City Council adopted a supplementary planning document specifying the requirement to produce travel plans for major developments in order to reduce car journeys, to reduce car speeds to improve

safety for pedestrians and cyclists, and to reduce freight movements (Leeds City Council, 2012b).

3.3.6 Leicester

Leicester is the largest city in the East Midlands area of central England and the 15th largest city in the UK. Initially Leicester developed as an important market town and then, during the industrial revolution, was a centre for hosiery manufacturing. Leicester has seen inward migration with its population increasing from 270,000 in 1994, to 293,000 in 2000 (Leicester City Council, 2000) to 329,900 in 2012 (Leicester City Council, 2011). This is in contrast to a population decline of 4.2% between 1971 and 1990 and a 10% decline in the number of people working in the City in the same period (Leicester City Council, 2000). This historic decline in population, particularly from the City Centre, led to an increase in the number of people commuting into the City (from 57,900 in 1971 to 69,770 in 1991) and a decrease in people travelling to work from within the City (from 119,490 in 1971 to 83,390 in 1991) (LTP1). Cycling levels have remained low despite the development of over 60 miles of cycling network infrastructure. Priority in the LTP2 in terms of cycling development was to complete missing links in the existing network, in particular the Green Ringway orbital route. In 2009 Leicester City Council commissioned WSP to use the PTOLEMY land use and transport model to determine the effect of a large proposed housing increase on urban congestion. Results showed that without intervention vehicle hours delay would increase in Leicester by between 15-40%, and that of the interventions considered, which included redistribution of employment centres, extension of park and ride facilities, or so called ‘smarter measures’ to deter car use in the City, measures that deter car use would be the most effective in reducing congestion (WSP, 2010).

At the time of the publication of the City's first Local Transport Plan in 2000, emphasis was being placed on the development of radial links between suburbs and the City Centre, and the development of three ring routes at various distances around the City Centre. The Leicester City Council LTP3 reported a 77% increase in cycling levels between 2003/4 and 2009/10, although this was at least partially attributed to better recording of numbers of cyclists. By 2009/10 cycling represented approximately 1.4% of total peak time trips into the City Centre (Leicester City Council, 2011). The ongoing cycling strategy presented in LTP3 concentrated on identifying low cost, high impact missing links in the existing cycle network, the integration of pedestrian and cycle movement in urban regeneration schemes, and the continued promotional and training activities.

3.3.7 Neath Port Talbot County Borough

Neath Port Talbot County Borough (NPTCB) is different from the other case study areas considered in that it is not dominated by a central urban area. NPTCB covers an area of 44,217 hectares, the majority of which is rural in nature (NPTCB, 2009). The topography of the NPTCB area is split into a narrow coastal strip to its south west which forms part of Swansea Bay, whilst the centre and north comprises of river valleys (Afan, Amman, Dulais, Neath and Swansea) separated by upland areas and mountains. The major population centre is in Port Talbot on the coastal strip with other population centres being in the lower Neath valley and Pontardawe. Historically, the coastal strip was dominated by large industry including steelworks, chemical works and refineries, with the industrial activity in the valleys comprising of mineral extraction. Today the coastal strip contains the majority of employment opportunities, with various manufacturing industries such as Tata steelworks and the local authority being major employers. The major east / west road link, the M4 motorway, main rail link (London – Swansea), and the deep water docks of Port Talbot are also located in the

coastal strip. Port Talbot is located 8 miles to the east of the major urban area of Swansea and approximately 30 miles west of Cardiff, and this proximity to the major urban areas of South Wales affects the movement of population within and through the area.

NPTCB contributes to the Regional Transport Plan for South West Wales (2010-2015) which provides a high level overview of regionally significant transport objectives. This includes a walking and cycling strategy which includes promoting behavioural change, establishing safe routes to link communities and urban network development (SWITCH, 2009) although there is no detail provided in the document on how these will be achieved. Despite not having a core central urban area within which cycling facilities can be concentrated, the area does have a relatively well defined cycle network but this is focussed on leisure/tourism.

3.4 Summary

This chapter provides an overview of the spatial analysis approach that was selected for use within this thesis including its origin within the EEP model and the development of space syntax into MapInfo. The advantages of space syntax are discussed together with the principles of the modelling procedure and how the configuration of space is quantified (Turner, Penn and Hillier, 2005). Techniques involved in the creation of the axial maps are presented along with issues and approaches developed to represent space differently (Turner, 2004; Manum and Nordstrom, 2013; Cahill and Garrick, 2008; Hillier, 1993; Turner, 2007; Dalton, 2007 and Penn et al., 1998). Justification for the selection of the six study cities/region is provided together with a description of each.

Chapter 4: Validation of the spatial analysis model for aggregated motor traffic flow

4.1 Introduction

One of the objectives of this thesis was to identify, test and improve a motor traffic flow model that can be used at a city/regional scale. In order to achieve this, integration values calculated by the spatial analysis model have been correlated with real motor traffic flow figures. If integration values are found to correlate well with real motor traffic flow figures, it can be concluded that space syntax procedures based in GIS MapInfo can be used to predict relative motor traffic flow within the modelled space and therefore be used to identify routes of high motor traffic flow. The same principles could then be applied to the movement of cyclists through the transport network. Opportunities to increase modal shift from car to bicycle in highly utilised areas can then be investigated in order to reduce carbon emissions and other impacts.

As described in the literature review (Section 2.10), it is costly and time consuming to set up and maintain traditional motor traffic flow models on at a city/region wide level as they can require the collection of vast amounts of data and require a high level of expertise to use them. This thesis aims to test a model that requires as little data as possible, provide meaningful and useful outputs that could work on a standard personal computer with commonly used software, and, therefore represent a cost effective city/region wide modelling platform. A step-by-step approach was used during the validation process to potentially limit the data collection required. Each step has been analysed individually to investigate its effectiveness in terms of modelling accuracy.

To undertake the validation process, as much reliable, valid motor traffic flow data as possible was collected from local authorities monitoring a wide range of roads. The relationship between measured motor traffic flow (independent variable) and model calculated spatial

integration values (dependent variable) was used to describe how well the model was able to predict real motor traffic flow figures. The aim was to achieve strong positively correlated variables – as motor traffic flow increases, integration values increase. The following statistical analysis was undertaken to investigate this correlation:

- **Linear regression** enables analysis of the direction and strength of the relationship between two variables (Moore, 1997). A regression line can be plotted which best fits the data, i.e. that goes through or is as close to as many of the data points as possible (Field, 2009). The direction of the relationship in this research should be positive, as one variable increases (i.e. integration value – dependent variable), the other should also increase (i.e. measured motor traffic flow – independent variable). The relationship should be strong, with points lying close to the line, with little scatter. The R^2 value is used to assess how good a fit the line of best fit actually is. This represents the percentage of variation in the dependent variable or how well the regression line fits the data (Field, 2009). A low R^2 (i.e. close to 0) indicates that there is little relationship between the dependent and independent variable (i.e. a poor correlation), whilst a high R^2 (i.e. close to 1) represents a good relationship between the two variables (i.e. a strong correlation). The integration value for each location where motor traffic flow data was available was obtained from the appropriate axial map and the regression value was calculated to evaluate the relationship between real motor traffic flow for the various tests undertaken. For consistency, linear regression analysis was run for all tests.
- **Spearman's rank correlation co-efficient (SRCC)** was undertaken to support linear regression analysis as it provides additional evidence where the relationship between data is not particularly linear. SRCC is a non-parametric test of statistical dependence between two variables, and it can be used for non-normally distributed data. Dependent (integration value) and independent data (real motor traffic flow data) is ranked and then Pearson's correlation is applied to the ranks. Pearson's correlation requires interval data

to provide an accurate measure of the linear relationship between two variables. By ranking data using SRCC, data is allocated to intervals allowing Pearson's correlation to be applied (Field, 2009). The sign of the SRCC indicates the association between the independent variable and the dependent variable. If both increase, the result is positive, if one increases and one decreases the correlation coefficient is negative. A score of zero indicates that there is no tendency for increase or decrease of the dependent variable as the independent variable increases. When the result is 1 (positive or negative), the data are perfectly correlated.

As the correlation between measured flow rates and calculated spatial integration values is influenced by human behaviour and other network characteristics, the R^2 and SRCC values are not expected to be as high as in physical processes. Linear Regression has been implemented as a means of evaluating the statistical correlation between measured and predicted motor traffic flow where the distribution of measured flows across the study area approaches normal. In order to account for instances where measured traffic flow is non-normally distributed, Spearman's Rank has also been implemented as a means of evaluating statistical correlation between measured and predicted traffic flows. A further discussion of this approach, including its limitations and alternative approaches is provided in Section 10.

4.2 Stage 1 – Validation of motor traffic flow model with basic flow data

Cardiff County Council provided data from loop detectors which counted motor traffic in both directions and were located at permanent, static positions on most major routes throughout the city. Loop detectors are induction loops under the road surface that forms part of a resonant circuit (Tillotson, 1984), motor traffic passing over them is automatically and continuously counted and recorded.

58 loop detectors were located throughout the city, mainly on A and B roads as illustrated in Figure 25. Motor traffic flow data was obtained for a period of eight weeks during the autumn for all 58 detector locations. This period was selected to represent typical flow patterns i.e. it excludes holiday times and key city events.

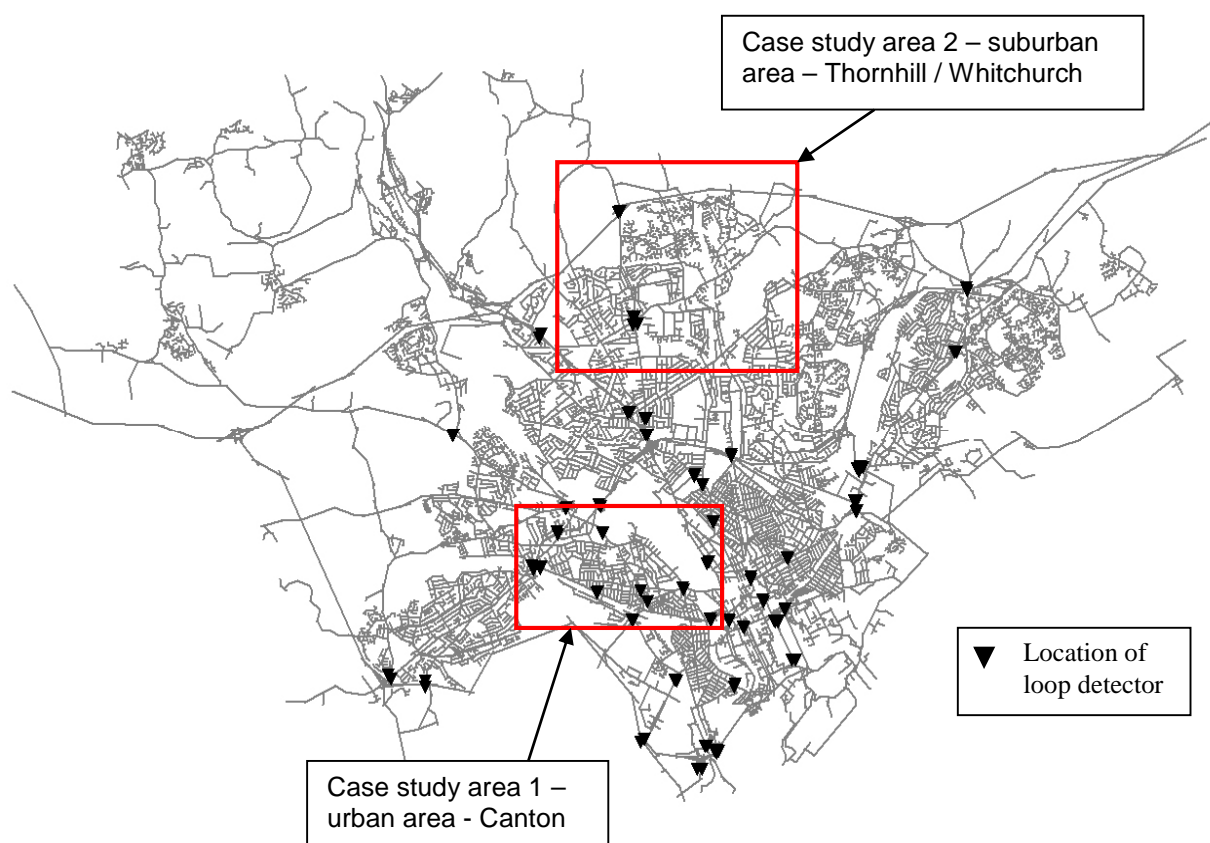


Figure 25 - Axial map of Cardiff including locations of loop detectors across the city and case study areas

Motor traffic flow data obtained was analysed using Analysis of Variance (ANOVA) in SPSS to remove errors recorded due to:

- Broken or damaged loops;
- Obscure weekly counts such as high volumes of motor traffic due to large sporting events.

A significance value of 95% was used to remove errors.

Data for loops which had viable results were combined to produce two directional average hourly motor traffic flow figures for each detector location. This temporal resolution of data

was satisfactory for the model as it considered relative differences between locations rather than the specific numerical value of the data. Using average hourly motor traffic flow figures also enabled comparable data to be used at different stages of testing the model.

For each individual location where average motor traffic flow figures were available, integration values from the axial map within the spatial analysis model were obtained. Linear regression analysis and Spearman's Rank Correlation Coefficient (SRCC) tests were carried out to analyse the relationship between average hourly motor traffic flow data from loop detectors and model calculated global integration values. Global integration is the value calculated when no modifications are made to the basic integration calculation procedures within the spatial analysis model.

It was anticipated that the initial correlation between average hourly motor traffic flow and basic global integration values may be weak due to count data not being available at this stage for a wide range of roads. Other factors such as motor traffic entering/leaving the city boundary and features that attract/detract road use are not accounted for within the basic spatial analysis model at this stage. As such, the scope of the validation process was expanded in a staged manner in order to account for these effects and to enable the motor traffic flow model to make predictions of necessary accuracy.

4.3 Stage 2 – Incorporating an increased range of motor traffic flow data

In Stage 1 of the validation process, motor traffic count figures were only available for major routes within the city of Cardiff and not for smaller roads. As a result of this bias in the initial data a relatively weak correlation between real average hourly motor traffic flow and integration values was expected because the fine network of lower motor traffic volume roads

was not accounted for. In order to address this, a second stage of validation which included monitoring data for roads with a range of integration values that were likely to have lower motor traffic flow volumes, for example small side streets in urban areas to cul-de-sacs located in suburban areas, was required.

Potential methods for incorporating this additional data into the validation process were tested on small case study areas of Cardiff as it was not feasible to gather average hourly motor traffic flow data at this fine level across an entire City or region. Manual counts and temporary Automatic Traffic Count surveys, using pneumatic 'tubes' were, carried out on a range of roads based on the different levels of integration value. Case study areas were chosen where a limited number of main routes enter the space and where some high level motor traffic count figures were available.

4.3.1 Case study 1 – urban area – Canton and Pontcanna

Case study 1 – ‘urban area’ included the compact urban areas of Canton and Pontcanna located near the centre of Cardiff as illustrated in

Figure 26. It is a densely populated, built up area of the city which is well defined, bound by four major roads, with loop detectors located on the main roads into the area.

Manual counts were undertaken by two personnel moving between two sets of ten data collection points for two days (8am-6pm) counting traffic (cars and vans only) travelling in both directions for five minutes at each location. Locations were selected to cover as wide a range of road integration values as practicably possible and also to minimise the time required to move between locations. All count locations within the sample area are illustrated on Figure 26.

Six temporary Automatic Traffic Count (ATC) surveys were positioned by Cardiff County Council (CCC) in requested locations in the area over the same period. The tubes work by recording the pressure changes in the tube from vehicles passing over them. The information was stored by the ATC equipment and downloaded at the end of the survey.

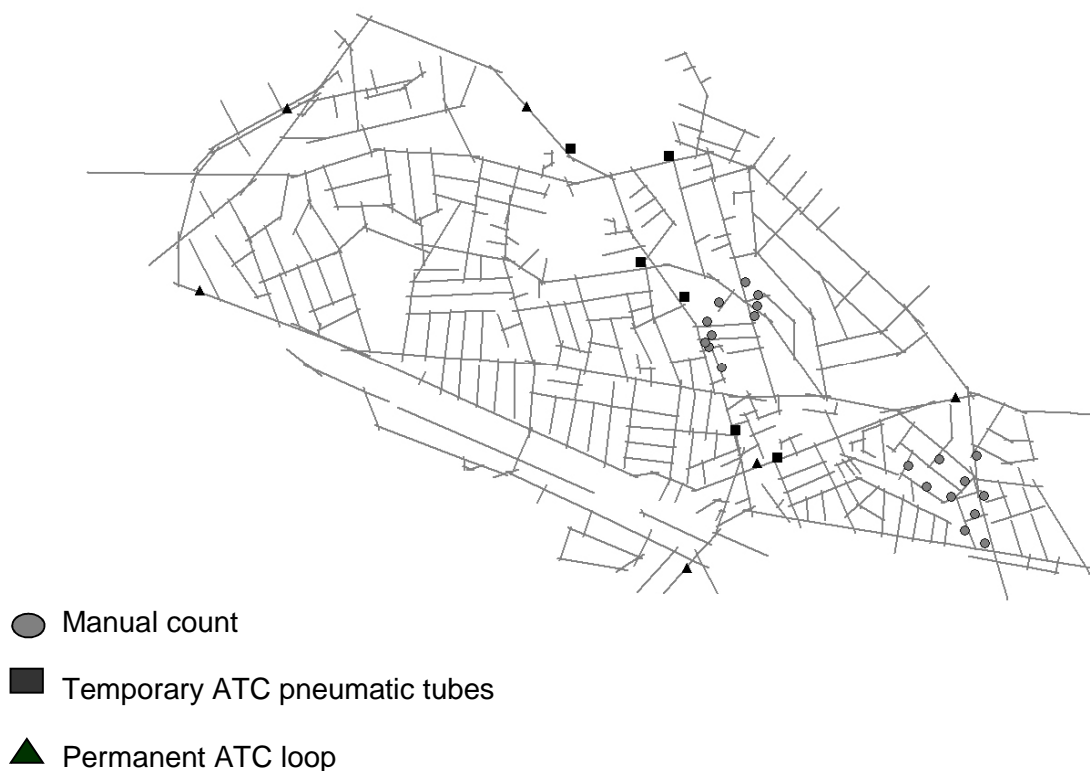


Figure 26 - Axial map of case study 1 - urban area illustrating count locations

Data was also obtained for six permanent ATCs located within the case study area. Therefore data for a total of 32 count locations was available (20 manual counts, 6 tubes and 6 loop detectors) in an area which included 360 axial lines. All results from motor traffic counts were converted to average hourly flow. As such a greater range of motor traffic flow figures for the area were available for model validation.

Two analyses were considered for case study 1 – urban area – Canton and Pontcanna:

- Global integration values were calculated when the whole axial map of Cardiff had been included within the calculations. This investigated the impact of looking at a sub-area of a larger space;
- Global integration values were calculated assuming the case study space was an isolated space, excluding the axial lines for the rest of Cardiff.

4.3.2 Case study 2 – Suburban area – Thornhill/Whitchurch

Case study 2 – ‘suburban area’, included the predominantly residential areas of Thornhill and Whitchurch, located at the northern edge of Cardiff. Data from 50 count locations was available from different counting mechanisms as illustrated in Figure 27 (40 manual counts, 3 tubes and 7 loops). Global integration values for the whole axial map of Cardiff were used for the calculation and provided additional evidence as to whether a broader range of motor traffic count data provided a better correlation between real data and integration values.

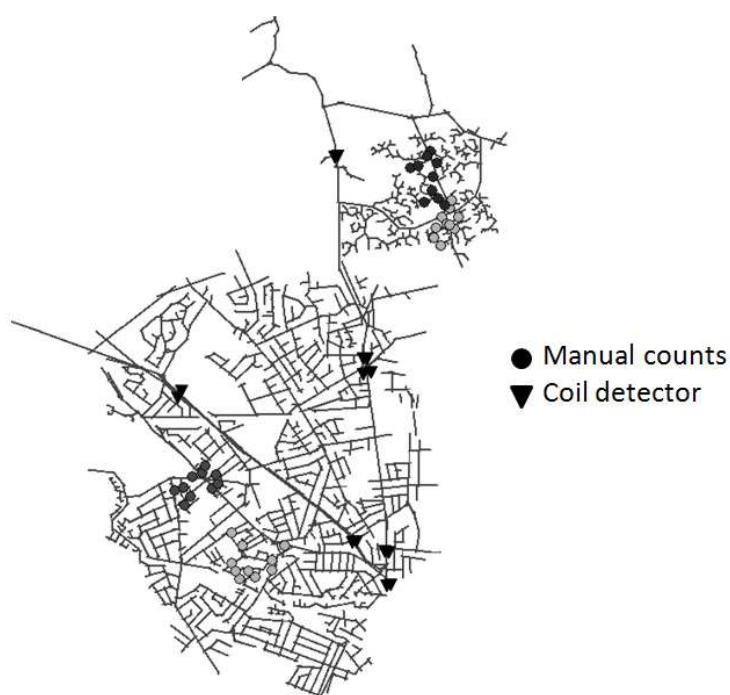


Figure 27 - Axial map of case study 2 – suburban area illustrating count locations

Global integration values for case study 2 – suburban area were used from the whole axial map of Cardiff and as such investigated the impact of looking at a sub-area of a larger space.

4.3.3 Extending the sample across the city

The next step was to obtain additional manual counts in other areas of the city to identify whether incorporating further measured flow data from roads with a broader range of integration values into the calculations improved the correlation for the wider city area. Data from a total of 117 motor traffic count locations were available from across the city for a range of road types, the nature of these are presented in Table 3. The locations of the different counting mechanisms can be seen in Figure 28.

Table 3 – Motor traffic count data available for Cardiff

Type of count	No. of locations
ATC loops	48
Manual counts	60
ATCs tubes	9
Total	117

The whole of Cardiff was included within the axial map and the analysis. The global integration value at each point where survey data was collected was extracted from the axial map and the correlation between the two data sets was undertaken using the previously described statistical methods.

4.3.4 Application of radius integration

The spatial analysis model developed incorporated a feature that enabled different 'radius' assessments to be made to identify whether limiting the spatial analysis to a local integration

approach produced a more accurate correlation with real traffic flow values. The method of radius integration is described in Section 3.2.3. Radius integration allows for the integration focus to be displaced from the centre of the entire road network for the city to roads that are well integrated within their locality. This method is applied using different radius calculations that produce different, more localised integration values. These localised integration values are analysed against real motor traffic flow figures.



Figure 28 - Map illustrating motor traffic monitoring locations across Cardiff

Radius integration analysis was undertaken at the following spatial scales to investigate whether the radius facility provided a good correlation with real traffic flow:

- City wide with limited data points on main routes only;
- Small study area – urban.

Radius depth values of 3 and 7 were applied at both scales (Penn et al., 1998; Dalton, 1997; Turner, 2004).

4.4 Stage 3 – Application of weighting factors

The ability of weighting factors to address identified limitations within the space syntax approach, and therefore improve overall correlation values, was investigated. Weighting factors were investigated independently to identify the correlation between average hourly traffic flow figures and predicted flow figures.

‘Weighting factors’ enable various characteristics of the network infrastructure that may have a greater influence on the integration values to be included in calculations (Law et al., 2013; Kwan, 2003; Desyllas et al., 2003). The weighting approaches investigated allow the incorporation of a degree of real world complexity into what would otherwise be a relatively non-complex modelling approach, without committing the end user to a greatly increased burden of data capture or complex data manipulation. An effective weighting factor, or combination of weighting factors, could improve the correlation between average hourly traffic data and predicted integration values by incorporating a limited level of additional complexity into the model. The methodology used when allocating weighting factors needs to be replicable and consistent to give it validity.

Weighting factors investigated as part of this Thesis were:

- Boundary weighting – allowed the movement of motor traffic in and out of the mapped area to be represented within the space analysis model;
- Road weighting – allowed specific road characteristics that influence the potential attractiveness of a road to be represented within the space analysis model.

These weighting approaches and their application within the model are described in the following sections.

4.4.1 Boundary weighting

Traditionally, when using spatial analysis, axial lines for the area of interest are input and an area is dealt with in isolation with the model only incorporating the lines within the axial map created within the calculations. ‘Edge effect’ can be incorporated as discussed within Section 3.2.3 which allows an estimation of incoming and outgoing motor traffic based on the surrounding configuration of the space, although this requires significant extra time commitment when considering urban scale spaces. Without including external spaces and associated movement, axial lines at the edge of an axial map are less integrated (i.e. have fewer connections) than those within the centre, and non-homogeneous population densities outside the area of study are not considered. However, in real situations this is not the case with potentially significant movement patterns in and out of mapped areas. When looking at the flow within an area the size of a city the influx of motor traffic adds a significant volume to internal motor traffic flows. For example, over 70,000 commuters in Cardiff live outside the city’s boundary (Cardiff County Council, 2011b) and this additional volume of motor traffic therefore needed to be incorporated into the analysis. The boundary weighting facility validated as part of this thesis, enabled road networks adjacent to the area of study to be incorporated into the calculations without physically drawing the axial lines for this extended area onto the map.

To add further functionality to the boundary weighting facility two levels of ‘depth’ were incorporated into the model. These were (i) connections and (ii) levels, both of which could be ‘attached’ to routes into and out of an area. A **connection** represented an unmapped road (i.e. a road that was outside of the specific area being modelled) that was linked directly to the axial map. A **level** represented unmapped roads leading from this connection. Connections and levels are illustrated on Figure 29. These can be attached to any road in an axial map. The

two depths provided the opportunity to represent a greater variation of incoming motor traffic at the boundary. Generally flow data is available for limited locations at the boundary of a city or region and this had to be considered when developing the methodology for assigning boundary weightings.

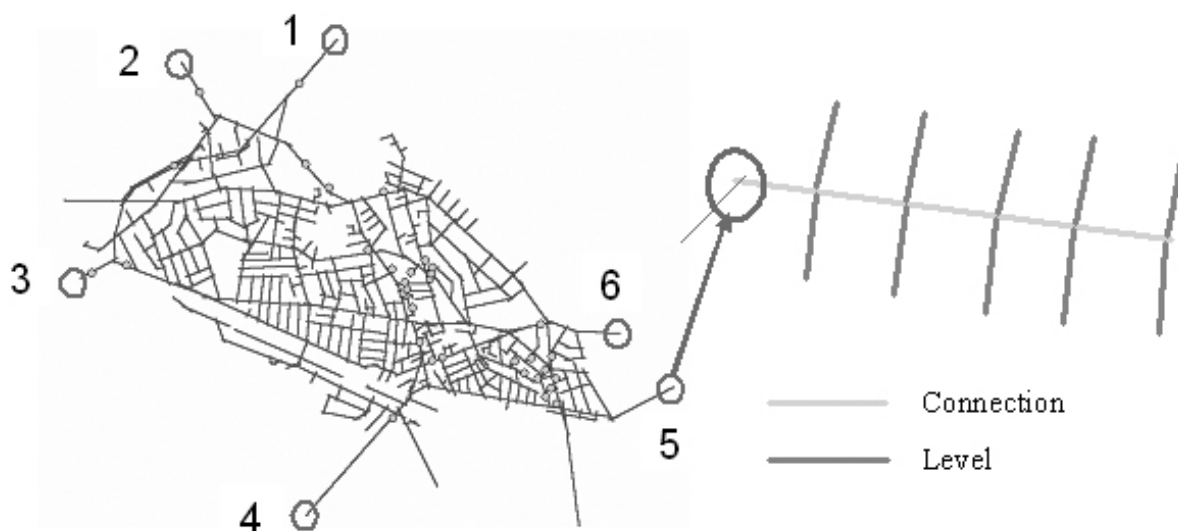


Figure 29 - Example of the boundary weighting facility

A replicable method both within and across regions had to be identified. Two main issues needed to be considered:

- Where should boundary weightings be allocated? There are many roads at the edge of a city or region that vary in flow. The method to be tested allocated boundary weightings to motorways, built up and non-built up roads;
- What weightings to use? – Real motor traffic flow data was available for limited locations at the boundary of a city therefore the method of allocating boundary weightings could not be reliant on the availability of real motor traffic flow figures. For example, the method could utilise the number of axial lines within the whole map and allocate flow figures that are proportional to this number.

In order to test possible boundary weighting methods and validate the model, comparisons between average hourly traffic flow and calculated integration values needed to be made. Methodologies for boundary weightings were tested on the case study 1 – urban area in Cardiff. Methods that demonstrated the strongest relationship between average hourly traffic flow and integration values were then tested on the whole of Cardiff and other cities in order to establish whether the method was valid at a larger scale and in other locations.

4.4.1.1 Classification of roads

Both boundary weighting and road weighting require consistent methods of weighting within and across cities. Key features of the motor traffic flow model are that it should be relatively easy to use and populate, and that it can be replicated both in the future and in other cities and regions in the UK and internationally, and this should be reflected in the choice of road classification system used. Discussions with local authorities took place to identify the most appropriate road classification system to use for boundary and road weighting. National road classification systems and fine scale network options were considered.

Fine scale network options included the possibility of mapping all features within the system that encourage or discourage motor traffic such as zebra crossings, surface quality and road width. Similar ‘weighting’ tests have been implemented by Law et al. (2013), Stähle (2012), Lin and Yu (2012) and Turner (2007) among others. This type of classification method could be applied when considering a small area of a city such as a neighbourhood, however, at a city or regional scale, the amount of data required is too vast and subjective to suit the criteria of the model under validation, i.e. the requirement that information should be able to be collected relatively quickly and easily.

Two broader road classification systems which are applicable on a city/regional scale and therefore replicable were chosen including:

- 1) Nationally allocated Motorways, A roads and B roads;
- 2) A network of Core (motorways), County (routes of significant importance) and Distributor (smaller key roads) roads as identified by the local authority as important routes within the City of Cardiff. This classification was devised by the Transport Planning Department of Cardiff County Council based on how roads are 'used' and was informed by local knowledge.

As the method to be used needed to be replicable, both in the future and in other areas, the classification system most suitable to be used in the model was motorways (M), A roads, B roads and minor roads as these are nationally classified and can be easily identified from a good road map. It was decided to elaborate on this classification to allow for distinction between speed limits as speed of motor traffic was considered likely to have a significant impact on the amount of on-road use by cyclists, together with other broader issues such as air pollution and accident rates. Therefore roads across the city were allocated to either:

- Motorway (M);
- Non-built up major roads (A or B roads) – speeds of more than 30 miles per hour;
- Built up major roads (A or B roads)– speeds 30 miles per hour or less;
- Minor routes.

4.4.1.2 Boundary weighting tests on case study 1 – urban area

Case study 1 - urban area was used to test the boundary weighting methodology as it is a well defined area, with a limited number of major roads leaving and entering it. The road network within the area was represented by 360 axial lines. Data for 35 locations was used at this stage including 20 manual counts, 6 ATC tubes and 9 ATC loops. The area had been expanded

slightly from initial tests to include main routes into the area, which accounted for the extra data. The locations of data collection points can be seen in Figure 29, including the six main boundary routes for the area. A number of combinations of connections and levels were tested on the six main routes into the area for which data was available, as illustrated in Table 4. These are the major routes into and out of the area i.e. motorways, A or B roads. Boundary weightings were assigned to the end axial line at the boundary for each road that is classified as an M, A or B road.

Table 4 – Table illustrating flow data for all major routes leading in and out of the case study area

No.	Road name	Location in Figure 29	Hourly traffic count (av.)	Percentage of overall flow movement
1	Western Avenue West of Taff Bridge	1	2,559	26
2	Cardiff Road North of High Street	2	1,631	17
3	Cowbridge Road East	3	2,408	24
4	Leckwith Road south of Lawrenny Avenue	4	1,434	15
5	Wood Street Bridge	5	416	4
6	Lower Cathedral Road	6	1,362	14
	Total traffic count (in and out of area)		9,810	100

Fifteen boundary weighting methods were assessed, applying different connection and level figures to the roads indicated in Table 5. The connections and levels described were applied to each of the six boundary locations in the case study 1 – urban area. Figures used to weight connections and levels in tests 1 – 6 used real motor traffic flow figures collected from the six boundary locations. This was not ideal as it is unlikely to be replicable at a city/region wide scale due to a lack of data. Tests 7- 15 used methods that were replicable for any axial map and were not reliant on real flow data. Tests 7 – 10 used independent, round numbers that did not relate specifically to the map.

Table 5 - Table illustrating boundary weighting tests undertaken for each case study area

Test	Connection weighting figure	Level weighting figure
1	Hourly traffic count	None entered
2	Half of the hourly traffic count	None entered
3	Half of the hourly traffic count	Half of the hourly traffic count
4	Double hourly traffic count	None entered
5	Five times hourly traffic count	None entered
6	10% hourly traffic count	10% hourly traffic count
7	1000	1000
8	100	1000
9	1000	None entered
10	100	None entered
11*	Radial distance (miles) from axial line (calculated as 1% of number axial lines in whole map).	None entered
12*	Radius distance (miles) from axial line (calculated as 0.5% of number axial lines in whole map)	None entered
13*	Number of axial lines within a 1 mile radius	None entered
14*	Number of axial lines within a 1 mile radius	Number of axial lines within a 1 mile radius
15*	None entered	Number of axial lines within a 1 mile radius

Tests 11 – 15 used data that related the boundary axial lines to the axial map as a whole and are therefore replicable. The weighting factors used were associated to the number of axial lines in the direct vicinity of the axial line to be weighted from the larger axial map of Cardiff. This method enabled the density of the area surrounding the axial line to be considered whilst providing a replicable method for estimating the incoming motor traffic to be used to provide a weighting, similar to the ‘Edge effect’ method (Section 3.2.3). The number of axial lines within the urban case study area was used as a starting point - 360. A percentage of this was then used to calculate a radius distance around the axial line. In test 11 this was 1% - 3.6 miles, and test 12, 0.5% at 1.8 miles. All axial lines within a radius of each distance were then

counted. Axial lines within the case study area were excluded as they were already included within the integration calculations. The connection and level values that have been used in the fifteen tests are presented in Table 6 these are based on the methods described in Table 5 above.

Table 6 - Table illustrating the connections and levels applied within each test case for case study 1 – urban area

Test	Western Avenue		High Street		Cowbridge Road East		Leckwith Road		Wood Street		Lower Cathedral Road	
	C	L	C	L	C	L	C	L	C	L	C	L
1	2559	1	1639	1	2408	1	1434	1	416	1	1362	1
2	1280	1	815	1	1204	1	717	1	208	1	681	1
3	1280	1280	815	815	1204	1204	717	717	208	208	681	681
4	5118	1	3262	1	4816	1	2868	1	832	1	2724	1
5	12795	1	8195	1	12040	1	7170	1	2080	1	6810	1
6	256	256	164	164	241	241	143	143	482	482	136	136
7	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
8	100	100	100	100	100	100	100	100	100	100	100	100
9	1000	1	1000	1	1000	1	1000	1	1000	1	1000	1
10	100	1	100	1	100	1	100	1	100	1	100	1
11	5291	1	4751	1	3889	1	4020	1	4477	1	4677	1
12	1407	1	1325	1	1066	1	849	1	1133	1	1433	1
13**	411	1	484	1	400	1	152	1	599	1	503	1
14**	411	411	484	484	400	400	152	152	599	599	503	503
15**	1	411	1	484	1	400	1	152	1	599	1	503

4.4.1.3 Boundary weighting for Cardiff

Following the completion of boundary weighting tests on case study 1 – urban area, tests were carried out on the whole of Cardiff. The road network of Cardiff was represented by 7,731

axial lines. Motor traffic flow data was available for 117 locations across the city on a range of road types as an additional data set was obtained for the same dates for extra locations from the county council. The count locations at the edge of the City were identified as M, A or B roads and these were also further classified as non-built up (>30mph) and built up (30mph or less). Boundary weightings were tested at boundary locations in order to generate a more valid correlation between integration values and average hourly traffic flow figures.

The tests undertaken, using the same principles as for case study 1 – urban area are presented in Table 7. Tests 1, 2, 10 and 11 used real traffic flow data and may not be replicable within other areas where motor traffic flow data is not available. Test 3 used global integration values calculated by spatial analysis from the axial map. Test 12 used figures proportional to the number of axial lines within the map, both methods therefore being replicable. This was also true for tests 4-9 which used independent figures related to the size of the axial map related to the authority classified core network and county network within the city as described in Section 4.4.1.1.

4.4.2 Road weighting

The final weighting method to be evaluated was road weighting. There are a number of characteristics of a road that can act as an incentive or deterrent for its use by motor traffic and other modes. These features can have an effect on the decision to use a route and therefore on total motor traffic flow. The model was modified such that it could incorporate features such as road type, road width and road furniture, such as zebra crossings, speed bumps and traffic lights into the integration value calculated. For example, where a road is better integrated into the network than an adjacent route it is currently assumed to be used more by motor traffic. However, if the more integrated road has speed bumps installed these will act as a deterrent to

motor traffic resulting in lower traffic levels than initially predicted by the model. By enabling road characteristics to be incorporated into the calculation road weighting could account for such effects.

Table 7 - Table illustrating the boundary weighting tests undertaken for Cardiff

Test	Sample locations	Connection weighting figure	Level weighting figure
1	11 loop detectors at boundary of city	Hourly traffic count	None
2	11 loop detectors at boundary of city	Double hourly traffic count	None
3	11 loop detectors at boundary of city	Global integration value from Cardiff map x 10,000	None
4	10 locations on 6 core 4 county	5000 for core 2000 for county	None
5	10 locations on 6 core 4 county	5000 for core 2000 for county	5 for core 2 for county
6	M roads – 3 A roads – 8 B roads – 2	M roads – 5000 A roads – 2000 B roads – 1000	M roads – 5 A roads – 2 B roads – 1
7	10 locations on 6 core 4 county	5000 for core 3000 for county	5 for core 3 for county
8	10 locations on 6 core 4 county	10,000 for core 4,000 for county	5 for core 2 for county
9	10 locations on 6 core 4 county	5,000 for core 2,000 for county	10 for core 4 for county
10	18 locations on M and A roads at the boundary of the city	Hourly traffic count	None
11	18 locations on M and A roads at the boundary of the city	10% of hourly traffic count	None
12	M roads – 3 NBU – 12 BU – 0	M roads – 1% of axial lines whole city NBU – 0.5% of axial lines within whole city BU – 0.25% of axial lines within whole city	M roads – 0.1% of axial lines whole city NBU – 0.05% of axial lines within whole city BU – 0.025% of axial lines within whole city

Different options for weighting roads within motor traffic flow modelling have been discussed within the literature review (Section 2.11) and opportunities to weight roads according to road width and/or features such as zebra crossings and speed bumps were considered. However, following discussions with local authority staff and some preliminary investigations using GIS maps and site visits it was found that the level of data collection required was too great and would break the criterion that data for the final model should be relatively easy to collect and input.

As an example, the collection of road widths as a possible weighting factor was initially considered. However, there were many variables affecting road width including parked cars, dual/single carriageways, presence of a central reservation, hard shoulders and turning lanes. These varied throughout an area and also along a single axial line/road. Certain features, particularly parking varied significantly during the day. To undertake data collection at this level of detail would be too time consuming and expensive for this type of urban scale model. As such it was decided that the UK wide road classification systems (as discussed in Section 4.4.1.1) would be used to assess the use of road weightings for replicability and simplicity.

4.4.2.1 Road weighting for Cardiff

The road weighting methodology was only tested on the whole axial map of Cardiff as there were very few motorways or principal routes within the smaller case study areas, therefore analysis of this weighting method at a smaller scale would not provide useful results. Figure 30 illustrates the axial map for Cardiff with the roads classified as motorways, principal routes and minor routes shaded.

Data from 148 motor traffic monitoring points was available for this analysis including loop detectors, manual counts and ATC data together with county motor traffic flow data for an additional 34 sites across the city. Data was collected from key routes, strategic counts, screenline sites and from within the central area of the city.

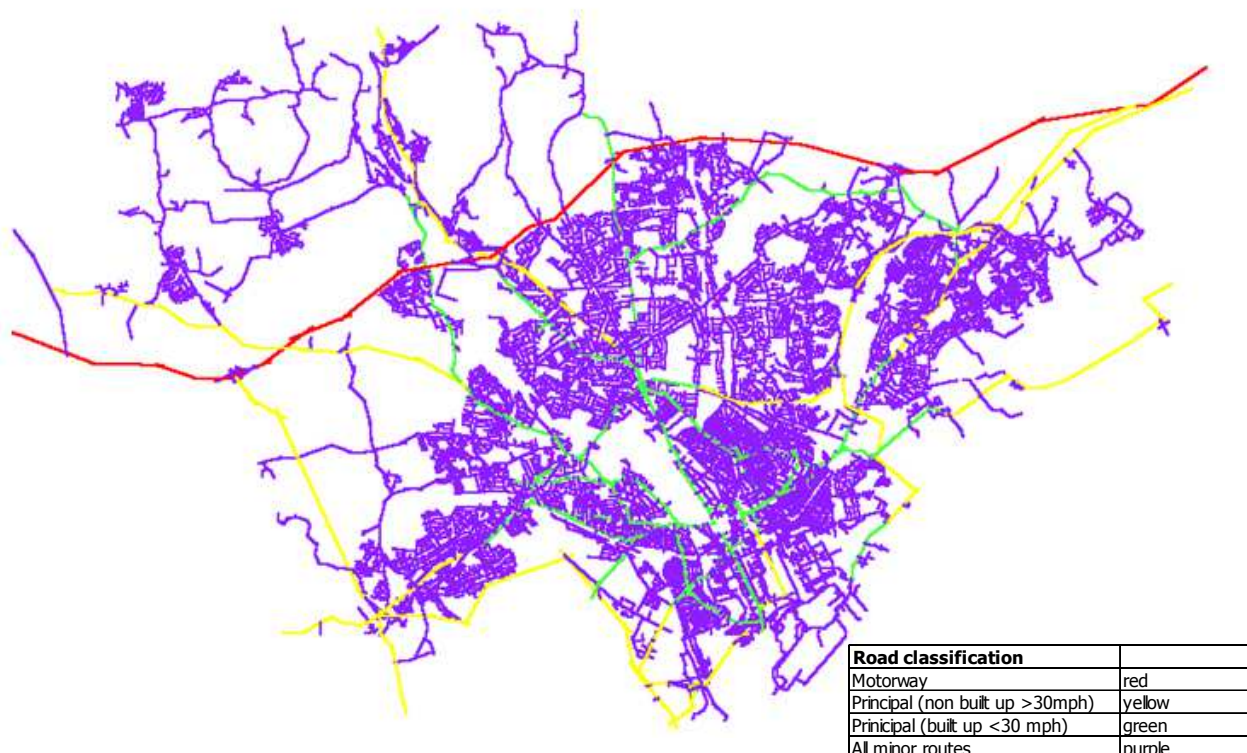


Figure 30 - Axial map of Cardiff illustrating classified roads

Three road weighting tests were applied to four different sets of integration values from previous tests. These four sets of integration values were chosen due to the variation of the source of the information and ease of data acquisition. These include:

- 1) Original global integration values with no boundary weighting;
- 2) Global integration values calculated from boundary weighting using County and Core roads (test 5 in Table 7);
- 3) Global integration values calculated from boundary weighting based on M, A and B road weightings (test 6 in Table 7);

- 4) Global integration values calculated from boundary weightings based on M, BU and NBU road weightings (test 12 in Table 7).

The three sets of road weighting applied are described in Table 8 below. Each axial line that was classified as each of the road types were weighted using the figures illustrated in the table below. These weighting figures are based on the relative importance of each road type as expressed by the road classification. In the interests of limiting data requirement for this weighting method the numerical range of values utilised is arbitrary. However, a possible more data intensive approach is discussed in Section 10. Tests were undertaken to identify an appropriate set of values that were large enough to impact on the results but were not too large to produce null results.

Table 8 - Table illustrating the classification of road types and different road weightings implemented

Road type	Road weighting test		
	1	2	3
Motorway	4	5	3
Non built up Principal route >30mph	3	3	2
Built up Principal route ≤ 30mph	2	2	1.5
Minor routes	1	1	1

Tests with and without boundary weightings were included because if boundary weightings did not improve integration values when road weightings were applied then it would be less time consuming and require less data to run a basic global integration calculation without boundary weightings.

Tests were undertaken using core and county roads for Cardiff, but this information may not be available in other areas and was therefore not the most favourable option due to a lack of

replicability in other areas. M, A and B road classifications are available for all roads within the UK and is therefore replicable if results from the boundary weighting tests showed an improvement on global integration values using this classification. This is also true for built up and non-built up roads. Each of the tests was applied using the three integration road weightings discussed in Table 8 above.

4.5 Test preferred correlation method on other cities/region

The final stage of the validation process was to test the most successful method from Stage 3 (i.e. the modelling techniques with the most successful weighting methods) on three other cities/regions. Motor traffic flow figures were obtained for two city/regions, namely, Leicester and Neath Port Talbot County Borough (NPTCB).

Results were also compared to predictions from SATURN provided by the Quantifiable City model (phase II) – QCII model for Leeds as described in Section 2.11 (Van Vliet, 1981; Atkins and ITS, 2013). These results were provided by researchers from the University of Leeds as part of the collaboration work undertaken during the development of the EEP and QCII models (EPSRC GR/L77348/01) (Namdeo et al., 2002).

Table 9 illustrates the number of axial lines within each city/region and the motor traffic flow sample data available for comparison. It can be seen that Leeds and NPTCB contain the most axial lines. Leeds has a much denser road network compared to NPTCB which is distributed over a much wider area. Much less motor traffic flow data was available for the additional cities and regions than the original study city of Cardiff. For NPTCB and Leicester, data collection was limited to locations of standard fixed data collection points which were generally located on main routes within an area.

Table 9 - Comparison of data from case study cities / region

City/Region	Number of lines in axial map	Number of locations where traffic flow figures available
Cardiff	7,731	148
Leicester	4,520	32
Leeds	9,347	40
NPTCB	9,207	23

The SATURN (Van Vliet, 1981; Atkins and ITS, 2013) model for Leeds was used to compare with the integration values. 40 locations were selected throughout the city to cover a wide range of road types and flows. Predicted motor traffic flow figures from SATURN were correlated with those from the spatial analysis map for the city.

Global integration was run for each of the three cities/regions. Three tests were then carried out to compare motor traffic flow figures with integration values. These tests are based on the most replicable methods and data available which can be applied to all three additional case study city/region areas from the tests for the whole of Cardiff in Section 4.4.2.1. Therefore the tests undertaken included:

- Global integration with no weighting;
- Global integration values with road weightings associated with motorway/non built up/built up from test 2;
- Boundary weighted global integration values with M/A/B roads weighted as in test 6 in Table 7 together with road weightings for motorway/non built up/built up routes;
- Global integration values calculated using boundary weightings using % axial lines and road weightings on M, BU and NBU (test 12 in Table 7).

M, A and B routes across the test areas were identified and these were used for boundary weighting locations. These routes were classified using the motorway, non-built up and built up system to allocate road weightings. Analysis was then carried out for each of the three tests described above for each of the three additional case study city/regions to evaluate transferability of the methodology that was applied most successfully in Cardiff.

4.6 Summary

This chapter describes the stepped data collection process used to test the ability of space syntax model to predict real traffic flow at an urban scale. It describes the collection of basic flow data and testing the validation process on case study sub-areas of Cardiff with increased data sets. Radius integration was tested to identify whether displacement from the centre of the road network to localities was found. The application of boundary and road weightings were described to attempt to improve the correlation values. These allow a degree of real world complexity into a relatively non-complex model. Roads were classified to allow these tests using a replicable method to enable transferability. Tests were run for different boundary weighting methods on both a case study sub-area and on the whole city. The road weighting method was tested on the whole of Cardiff. The methodology for the most successful methods were then tested on three other city / regions, comparing results with both real motor traffic flow data and data generated from SATURN. The results are presented in Chapter 5.

Chapter 5: Results from the validation of the spatial analysis model for aggregated motor traffic flow

5.1 Introduction

The aim of this Chapter is to present the test results for the implementation of a spatial analysis model for vehicular road traffic flow in cities. The results are presented in the same order as the process described in Chapter 4, namely:

Stage 1 – Correlation of integration values and basic motor traffic flow data from loop detectors;

Stage 2 – Incorporation of an increased range of motor traffic flow data into Stage 1 to include analysis of:

- case study 1 - urban area (Canton and Pontcanna);
- case study 2 - suburban area (Whitchurch and Thornhill);
- city wide;
- radius integration.

Stage 3 – Assessment of the effect of weighting factors on correlations, including:

- boundary weighting;
- road weighting.

Stage 4 – Testing of preferred correlation method on other cities/regions.

This staged approach was taken in order to identify the process that would provide the best balance between achieving a satisfactory correlation between integration values and motor traffic flow data whilst trying to limit the amount of data and time required to establish a reliable and practical model.

Results are presented using graphs and tables, and also through thematic maps which present the integration values that were calculated using spatial analysis procedures graphically. The

integration maps are presented using the colour spectrum with red for high integration through orange, yellow, green, blue and purple, for low integration. The integration values calculated are relative to all other lines within the *same* map only. Integration values calculated for different maps or using different data are not directly comparable.

5.2 Stage 1 - Validation of motor traffic flow model with basic flow data

Following the removal of outlier results as described in Section 4.2, reliable data was available for loop detectors at 48 locations across Cardiff. Motor traffic flow data was converted to a two directional average traffic flow per hour for a 12-hour period to allow relative flow rates to be compared. The minimum flow within the sample was 554 vehicles per hour, the maximum was 4,091. A histogram presenting the frequency of average hourly traffic count is presented in Figure 31 below. The average hourly traffic count of the monitored locations was 1,807 with a median of 1,716.

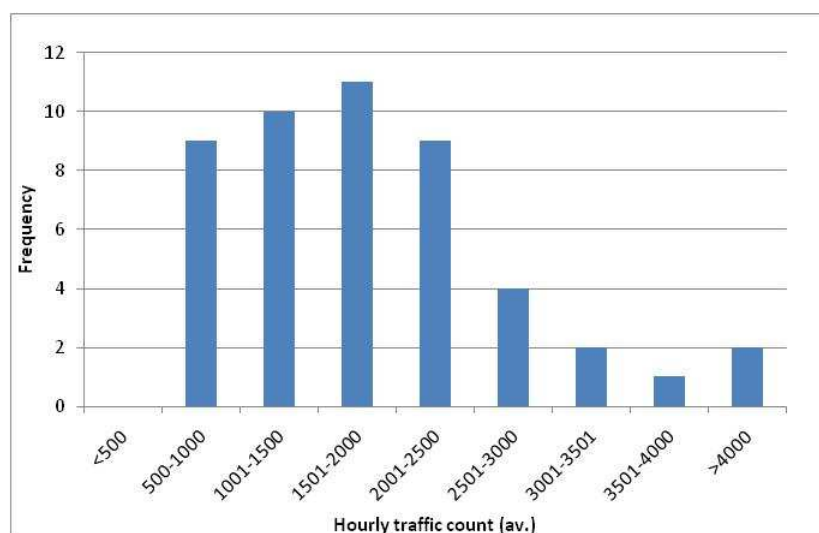


Figure 31 - Histogram illustrating average hourly motor traffic count at sample locations across Cardiff for Stage 1

Figure 32 shows the axial map for Cardiff indicating the range of global integration values calculated. The black triangles indicate the sampling points. Red lines indicate well integrated

routes, purple are relatively not well integrated. Both the average and median global integration value was 0.54.

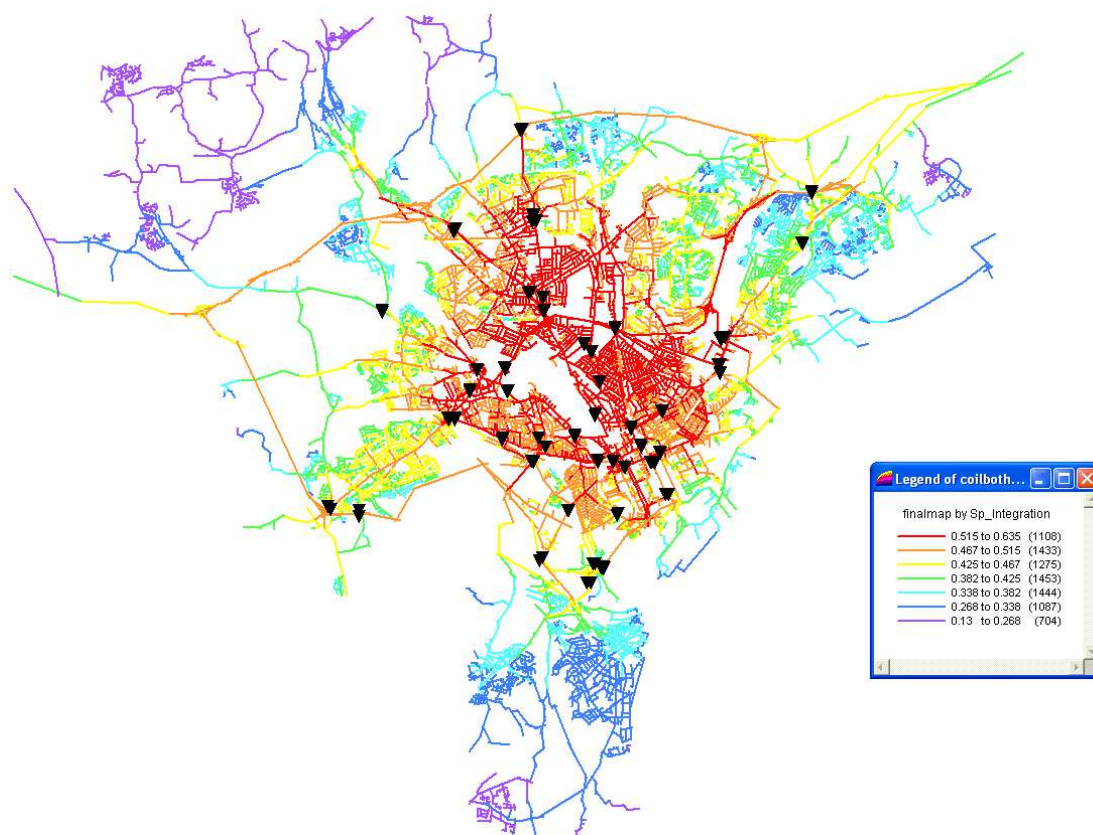


Figure 32 - Global spatial integration map for Cardiff motor traffic flow

Figure 32 illustrates that, as would be expected, the more integrated roads are located towards the centre of the map, i.e. towards the city centre, with less integrated routes around the periphery. Some of the major routes such as motorways around the edge of the city, particularly at larger junctions, are more integrated than nearby suburban areas as they have more connections.

Linear regression analysis was carried out to identify the relationship between average hourly motor traffic flow data obtained from the 48 loop detectors and the global integration value, with global integration being the value calculated when no modifications (e.g. weighting) were made to the standard integration calculation. Figure 33 illustrates that an R^2 value of 0.07 was

obtained, indicating that there was not a strong relationship between average hourly motor traffic flow data and global integration values using the basic spatial analysis model with a limited set of average hourly traffic flow data available from the local authority.

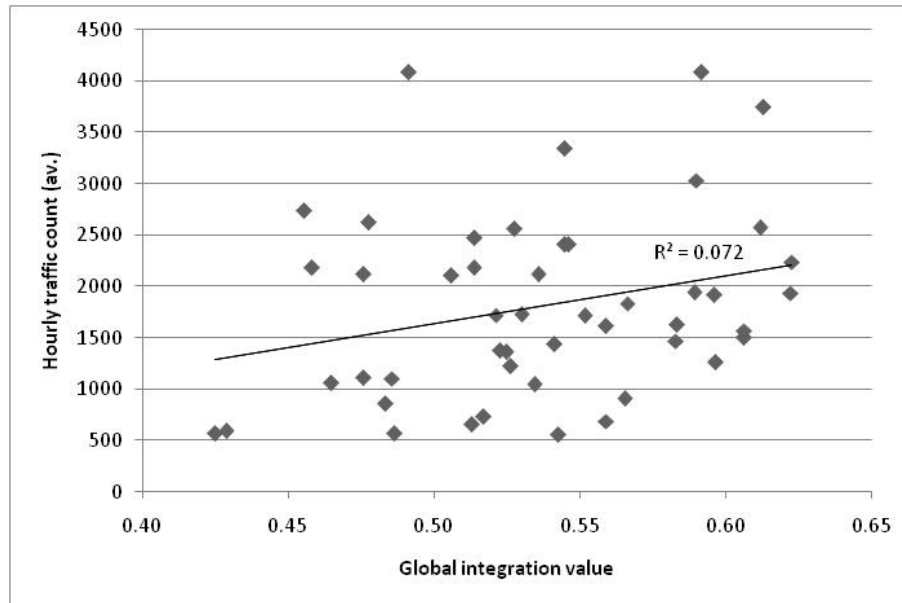


Figure 33 - Graph of global integration and average hourly motor traffic count data for 48 sample locations across Cardiff

Spearman rank correlation co-efficient (SRCC), which was significant at 0.05 level, gave a correlation coefficient between the global integration values and motor traffic flow data of 0.246 indicating a weak, positive correlation. This result corresponds with the R^2 value obtained above.

As discussed in Chapter 4, it was expected that correlation values obtained from the standard, unmodified spatial analysis model would be weak as (i) motor traffic flow figures were only available for major routes within the city and not for smaller roads i.e. the data set was limited, (ii) motor traffic entering the city boundary was not accounted for, and (iii) road features that might affect motor traffic flow were not accounted for. Further steps were undertaken in order

to address these limitations and to improve the correlation between the spatial analysis model and real motor traffic flow. The results for these are described below.

5.3 Stage 2 – Incorporating an increased range of motor traffic flow data

5.3.1 Case study results

Case study 1 – urban area – Data was available for 32 locations for the Pontcanna/Canton area within Cardiff as described in Section 4.3.1. The maximum average hourly motor traffic count was 2,110 vehicles per hour, with a minimum of 19. Twelve locations had an hourly motor traffic count of less than 100 vehicles per hour. The average hourly motor traffic count was 653 and the median was 388. Figure 34 illustrates a skew towards lower average hourly motor traffic counts.

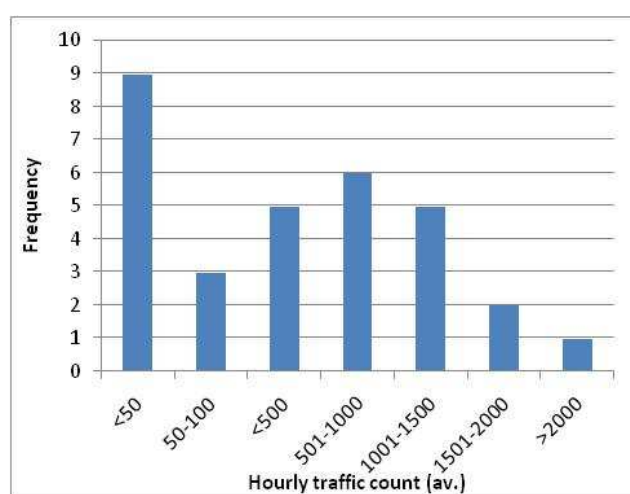


Figure 34 - Histogram illustrating average hourly motor traffic count at sample locations for case study 1 - urban area

The thematic map for the case study 1 – urban area, illustrating the range of global integration values used *from the axial map of the whole of Cardiff*, is shown in Figure 35. Sampling points

are indicated as described in Section 4.3.1. A visual assessment indicates that generally, the majority of the main routes within the area are indicated as being well integrated.



Figure 35 - Global spatial integration map for case study 1 - urban area when extracted from full Cardiff map

When considering the measured average hourly motor traffic count figures correlated with the global integration values calculated from the axial map of the whole of Cardiff a strong correlation is demonstrated (Figure 36).

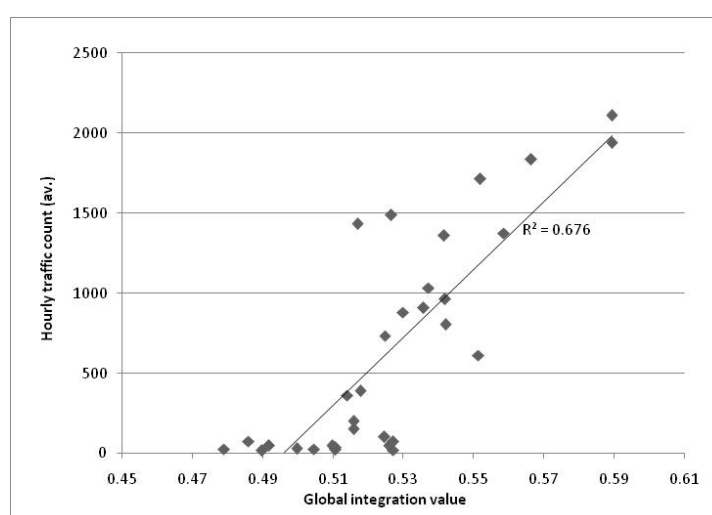


Figure 36 – Graph of global integration and average hourly motor traffic flow for a range of road types at 32 locations within case study 1 – urban area in Cardiff using global integration values from the axial map of the whole of Cardiff

Linear regression analysis of average hourly motor traffic count data with global integration values produced an R^2 value of 0.68, which confirms a reasonably strong relationship. This is supported by a SRCC of 0.8, which also suggests a strong, positive correlation.

Further analysis was undertaken on this data set to investigate differences between locations with higher and lower average hourly motor traffic flow. Figure 37 shows a reasonably strong relationship between average hourly motor traffic count and global integration values for locations with more than 100 vehicles per hour with an R^2 value of 0.65. This is supported by Spearman's rank correlation co-efficient of 0.85, which suggests a strong, positive correlation. However, on roads with less than 100 vehicles per hour (sample size 12, below the suggested figure of 20 for a regression analysis test) the R^2 value is only 0.016 (Figure 38) signifying a poor relationship. This indicates that the model may be able to predict motor traffic on roads of frequent higher flow levels but not for roads which have infrequent flow.

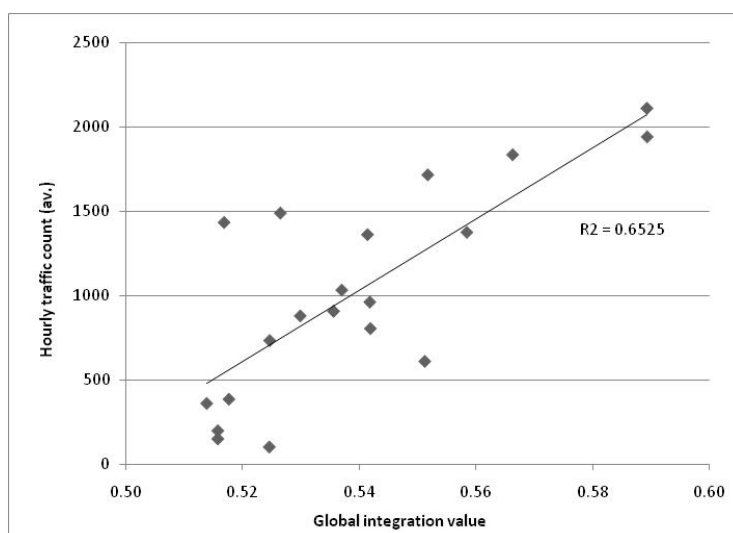


Figure 37 - Graph illustrating the correlation between global integration value and average hourly motor traffic flow for roads with more than 100 vehicles per hours within case study 1 - urban area of Cardiff

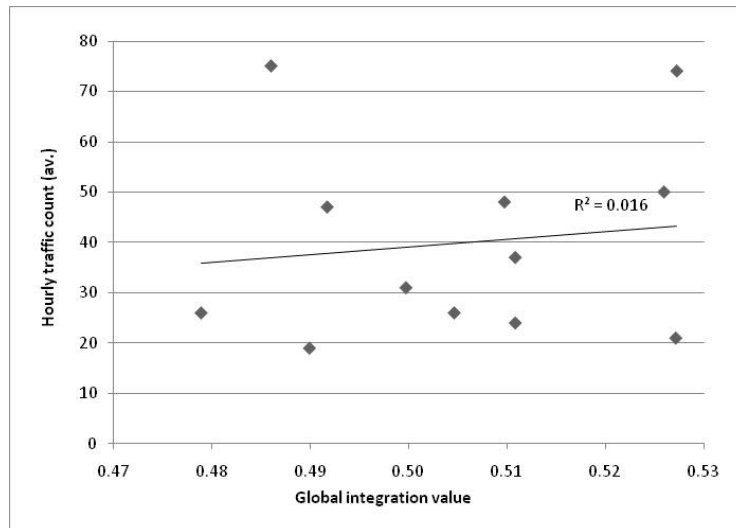


Figure 38 - Graph illustrating the correlation between global integration values and average hourly motor traffic flow for roads with less than 100 vehicles per hour within case study 1 - urban area

Further calculations were undertaken correlating well integrated roads (where the global integration values are greater than 0.53) with available motor traffic flow data. Here, the R^2 value was calculated to be 0.73 which indicates a strong relationship. For roads with a global integration value of less than 0.53 the calculated R^2 value was 0.13 suggesting a weak relationship, again suggesting that the model may not be capable of accurately representing motor traffic flows along roads with low motor traffic flows (i.e. that are poorly integrated). This is likely to be because motor traffic on more integrated routes are 'passing through' an area and is more consistent and therefore predictable, whereas motor traffic on less integrated routes is more specific to the location such as departing from a journey origin or moving towards a specific destination and is therefore inherently less predictable for individual journeys.

The thematic map for the case study 1 - urban area, illustrating the range of global integration values when the area is dealt with in isolation (excluding the rest of the axial map for Cardiff), can be seen in Figure 39.

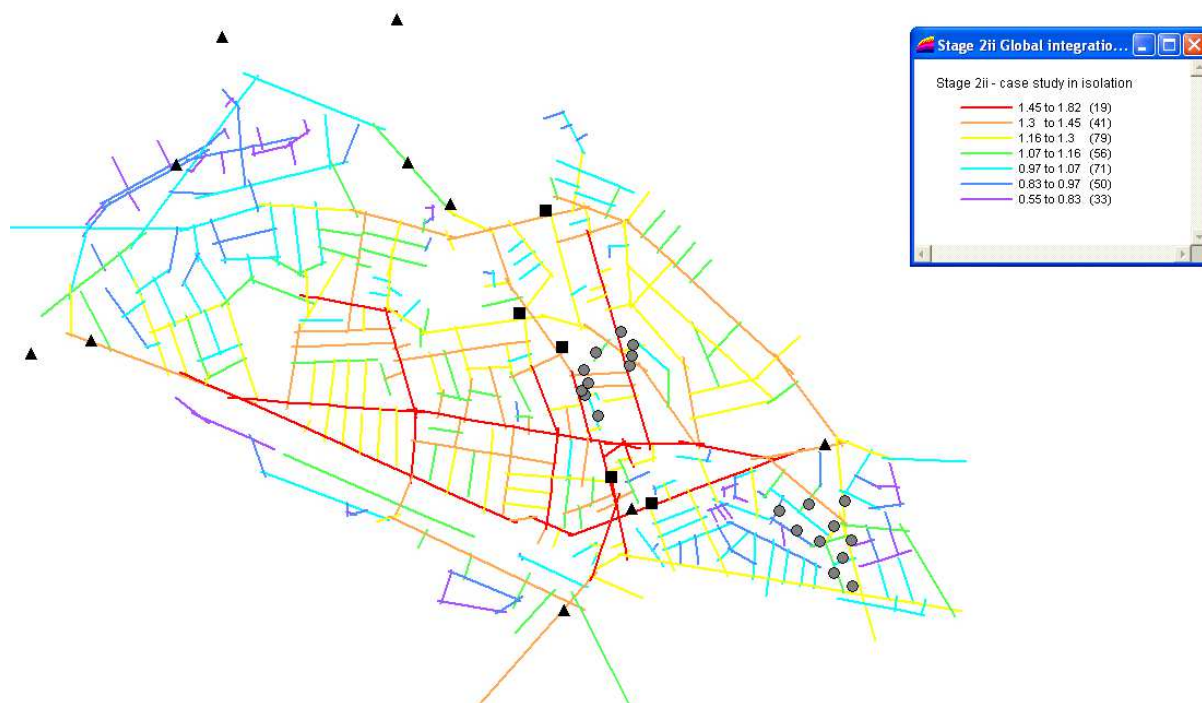


Figure 39 - Global spatial integration map for case study 1 - urban area when the area is dealt with in isolation

The relationship between global integration values calculated for case study 1 - urban area, when dealt with in isolation and average hourly motor traffic flow figures is weak, with an R^2 of 0.05 as illustrated in Figure 40. The SRCC was found to be significant at 0.01 level whilst results indicated a correlation of 0.41 which indicates a weak, positive correlation. This corresponds with the R^2 value obtained.

The relationship did not improve when considering low and/or high flow rates, with R^2 values of less than 0.1. Reasons as to why the basic model performs poorly for an isolated area may include incoming motor traffic into the isolated area not being accounted for a limited set of data and a narrow range of road types being present.

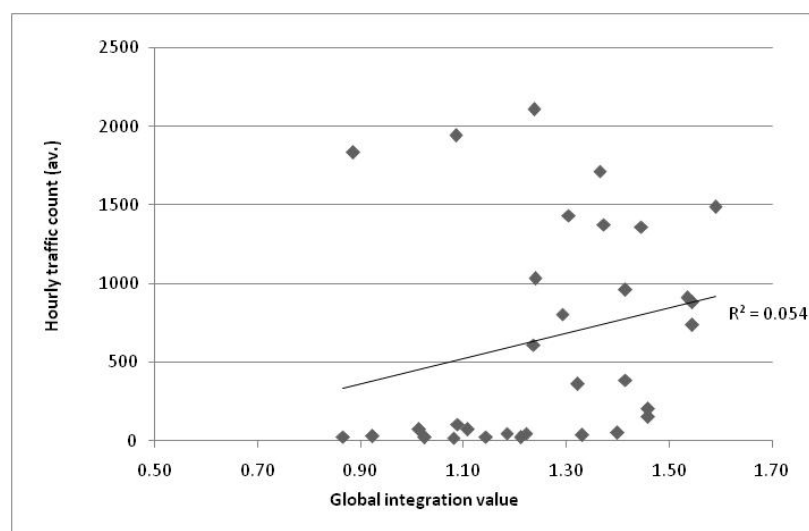


Figure 40 - Graph demonstrating the relationship between global integration values from case study 1 area in isolation and average hourly motor traffic flow for a range of road types at 32 locations within case study 1 - urban area

Case study 2 – suburban area - For the case study 2 – suburban area, Thornhill and Whitchurch, data for 50 locations were available. The sample covered a much larger area than case study 1 – urban area and included 1,113 axial lines. The maximum average hourly motor traffic count was 3,033 vehicles per hour, with a minimum of 6. The mean average hourly flow count was 517 and the median was 108. 24 sample locations had an hourly flow rate of less than 100 vehicles per hour.

The thematic map for the case study 2 – suburban area illustrating the range of global integration values used *from the axial map of the whole of Cardiff* can be seen in Figure 41.

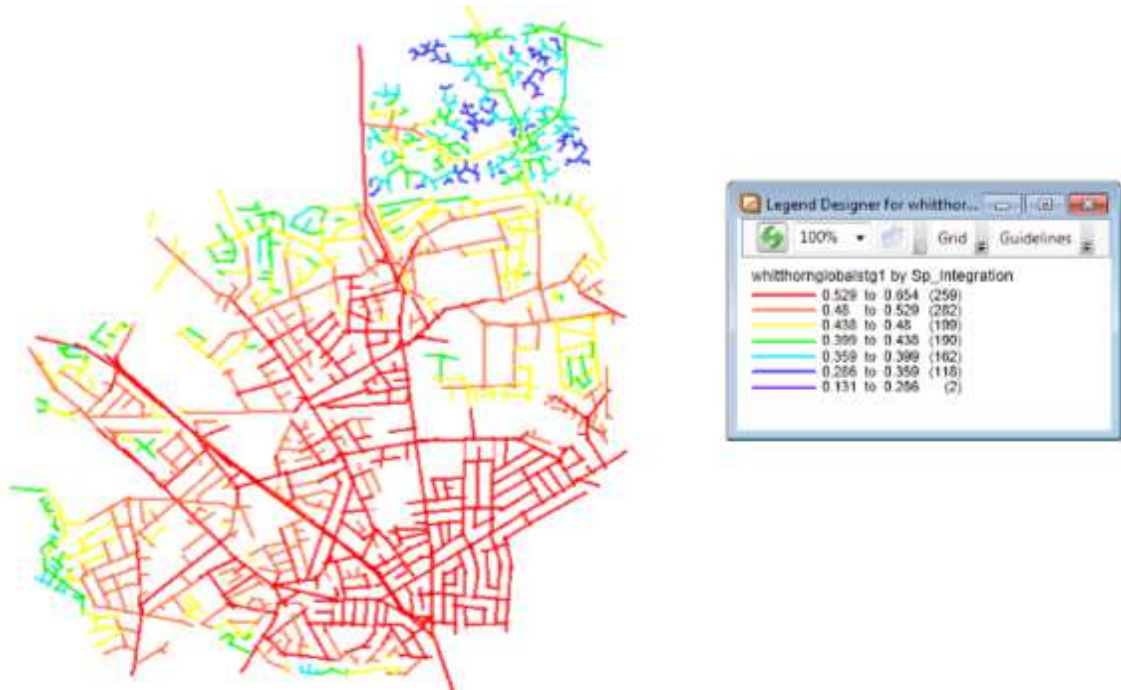


Figure 41 - Global spatial integration map for case study 2 - suburban area when extracted from full Cardiff map

Linear regression analysis of average hourly motor traffic count data with global integration values produced an R^2 value of 0.52 (Figure 42), which suggests a fairly strong relationship.

This is once again supported by a correlation co-efficient of 0.8, suggesting a strong, positive correlation. Analysis of case study areas demonstrated that by using a wider range of flow values within these specific areas a much improved correlation between average hourly motor traffic flow figures and global integration values was achieved. This was particularly the case for more integrated roads and roads with higher flows, *when taking into account the case study areas and the surrounding space* (represented by the axial map of Cardiff).

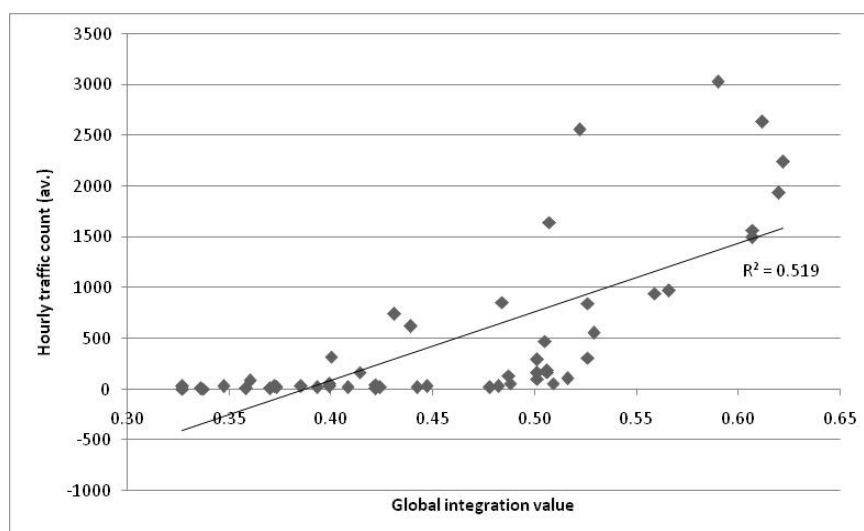


Figure 42 - Graph demonstrating the relationship between global integration and average hourly motor traffic flow for a range of road types for 50 locations within case study 2 - suburban area of Cardiff using global integration values from Cardiff axial map

When the case study space was dealt with in isolation the relationship remained weak. This reinforces the need to enable the model to consider motor traffic which crosses the boundary of the specific area under study from the surrounding area or to represent an extensive buffer network.

5.3.2 Extending the sample across the city

For this stage the data set was extended to 117 locations from across the entire city on roads with a range of vehicle flows from 6 vehicles per hour to 4,091 vehicles per hour. The mean average hourly traffic count was 947, with a median of 612. Flows of less than 100 vehicles per hour were recorded at 36 of the sampling points. Flows of more than 100 vehicles per hour were recorded at 81 locations.

The relationship between average hourly traffic count and global integration was found to be not very strong when all 117 count locations were included, resulting in an R^2 value of 0.295 (Figure 43). A correlation co-efficient of 0.632 was obtained which represents a moderate, positive correlation, which again corresponds with the results from the linear regression analysis above. Weak correlations are obtained when only considering roads with more than 100 vehicles per hour (R^2 of 0.20), or less than 100 vehicles per hour (R^2 value of 0.12). The results demonstrate that global integration values correlated only slightly better with higher motor traffic count figures.

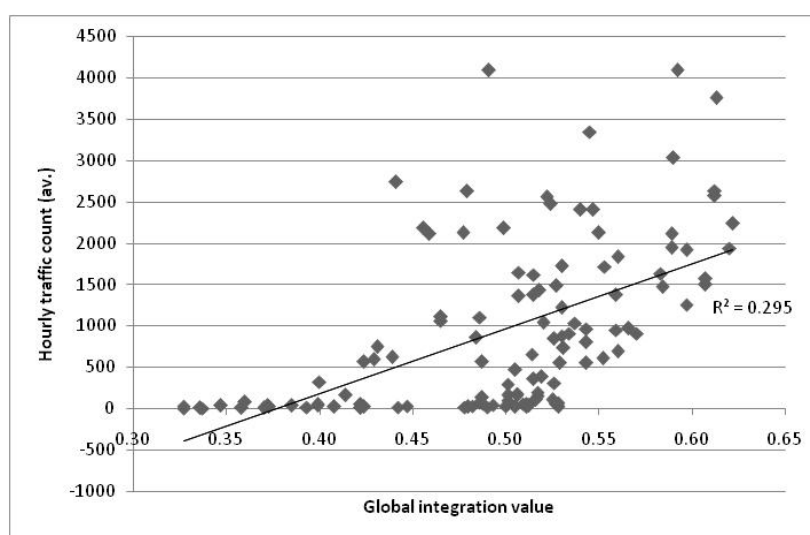


Figure 43 - Graph illustrating the relationship between average hourly traffic count and global integration for 117 locations across Cardiff

Applying the model to a case study urban area resulted in a higher correlation between global integration values and average hourly traffic flow figures when the broader, city wide area was considered within the integration value calculations i.e. when the case study area was considered as part of a larger space. However, when the case study area was considered in isolation from the surrounding area, correlation achieved was poor. Similarly, when the city wide area is considered as a large, isolated space (no data is available for outside the city), correlations are again poor. When considering the entire city a small increase in correlation

was found when data from more motor traffic flow points was available, however, not to the extent that the model could be considered functional for the intended purpose, and not to the extent that this additional data could compensate for the effect of modelling an isolated space. This confirmed that additional computational methods of improving the predictive capabilities of the spatial analysis model were required, as opposed to the inclusion of additional monitoring data.

5.3.3 Radius integration

Radius integration tests, as described in Section 4.3.4, were undertaken for the city and case study 1 – urban area (Canton and Pontcanna), to identify whether there was an improvement in the relationship between average hourly motor traffic flow figures and integration values by utilising this integration method. Radius integration 3 and radius integration 7, which represent a difference in depth from each axial line, were applied to the model for the two axial maps.

Radius integration results were calculated for the case study area in isolation and also for the city as a whole. Thematic maps for radius integration are shown in Figure 44 (Cardiff radius 3), Figure 45 (Cardiff radius 7), Figure 46 (case study 1 – urban area radius 3) and Figure 47 (case study 1 - urban area radius 7).

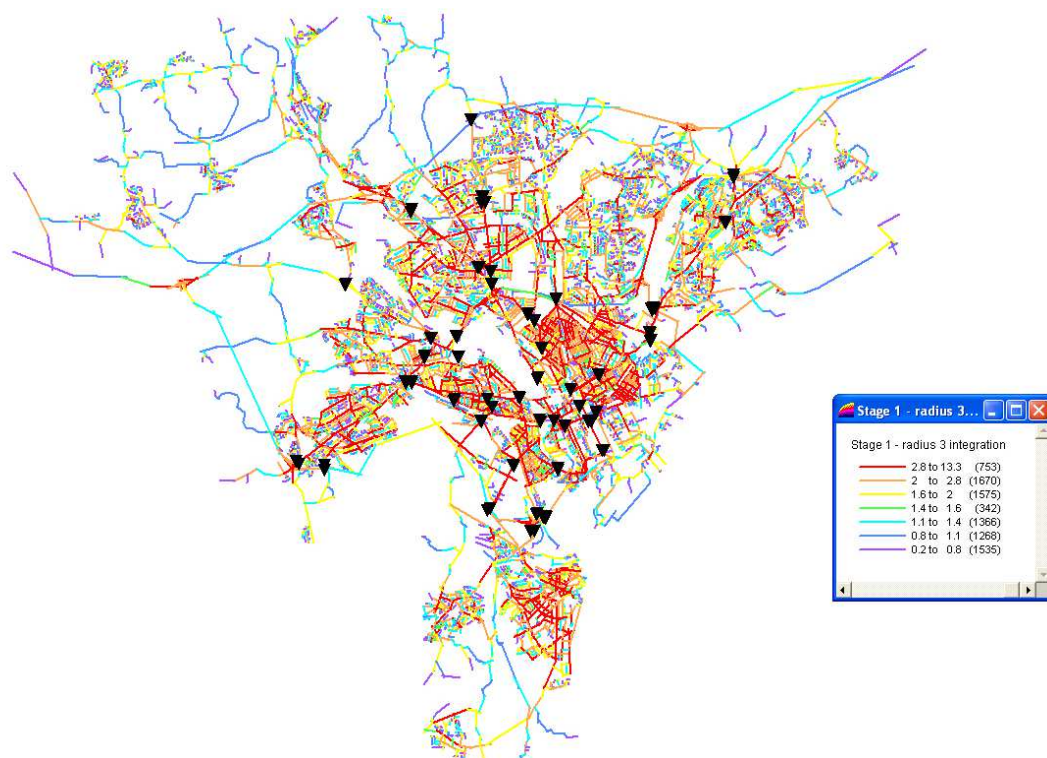


Figure 44 - Radius 3 integration map for Cardiff

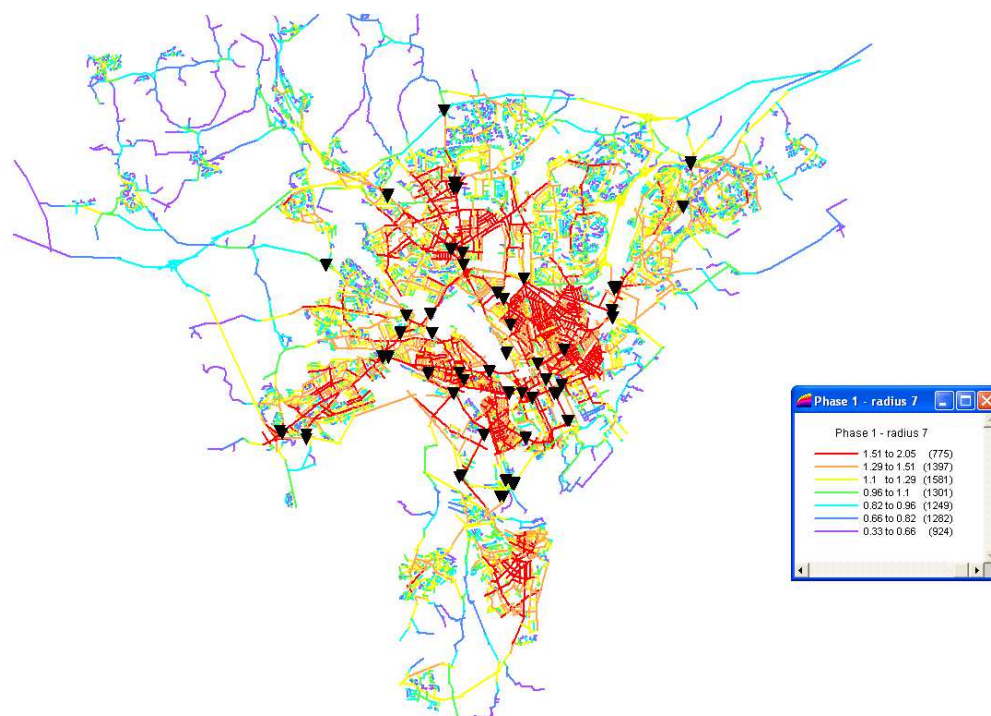


Figure 45 - Radius 7 integration map for Cardiff



Figure 46 - Radius 3 integration map for case study 1 - urban area



Figure 47 - Radius 7 integration map for case study 1 - urban area

On visual inspection, the maps produced using radius 7 calculations were more consistent with global integration, where the central area of the map was more integrated. Within the radius 3 maps, routes considered more integrated were more dispersed across the axial map and more 'locally' integrated routes i.e. spaces that have a higher number of connections in close proximity, are indicated to be well integrated.

A summary of the results of the radius integration tests for each stage is provided in Table 10. Regression analysis indicated that radius integration did not improve the relationship between motor traffic count data and integration values. Stronger correlations, as indicated by a higher R^2 value, were calculated using global integration than either of the radius integration calculations both when isolated (i.e. city wide) and non-isolated (i.e. case study area) areas were considered, and when the extended city wide data set was used. This result was also supported by correlation co-efficient results (Table 10).

Table 10 - Table illustrating differences between global and radius integration results

Stage	Test	Integration Method	R^2 value	Pearson's correlation co-efficient
1	City wide loop detectors	Global integration	0.295	0.246
		Radius 3	0.00	-0.059
		Radius 7	0.00	-0.018
2i	Case study 1 – urban area analysis	Global integration	0.68	0.8
		Radius 3	0.15	0.608
		Radius 7	0.19	0.513
2ii	Extending the sample range across the city	Global Integration	0.30	0.632
		Radius 3	0.12	0.502
		Radius 7	0.18	0.556

For Stage 1, weak, negative correlations were obtained. These improved when considering both the case study 1 – urban area and when extending the sample range across the city with moderate, positive correlations suggested. However, as the results of the radius integration calculations are all weaker than global integration calculations, it was confirmed that this was not an appropriate method to be used further in this study.

5.4 Stage 3 – Assessing the effect of weighting factors on correlation

5.4.1 Boundary weighting

5.4.1.1 Boundary weighting tests on case study area

As identified above, consideration of a space in isolation, whether it is city wide or a sub-area within a city, results in poor model performance as motor traffic flow crossing the boundary is not taken into account. Whilst considering the area being modelled as part of a larger space largely eliminates this effect, as demonstrated above where the case study – urban area is modelled as a sub-area of the larger city wide space, accommodating this adds greatly to the volume of data required, particularly if city wide or regional areas are being considered. Collection of data on this scale may not be practicable, and does would not comply with the initial research goal of validating a model does not incur excessive data collection burdens. Therefore, some other means of allowing for motor traffic movement across model boundaries was required.

Previous research, as described in the literature review (Section 2.11) (Turner, 2007; Cahill and Garrick, 2008) have used buffer zones around areas under investigation to represent movement crossing the boundary within small scale axial maps. Turner (2007) created an axial map with a buffer zone of 3km by 3km for a study are of 1km², a 9:1 ratio of additional

modelling required to represent external space. Cahill and Garrick (2008) created a buffer area of 8.05km for a small sample area in Cambridge, Massachusetts. This indicates that on a small scale, extending the axial map to contain a catchment area does not require a significant additional time resource to create the buffer zone axial map but when considering larger urban areas of over 100km², the additional human resource to represent the edge effect would be large and time consuming to create, which does not support the aims of creating a parsimonious model. Therefore, within this study utilisation of boundary weighting as an alternative to the buffer zone effect will be tested, as described in Section 4.4.1. Initially, boundary weighting was tested on case study 1 – urban area of Cardiff (Canton and Pontcanna). Motor traffic flow data for 35 locations was available. Ideally the methodology for boundary weighting should be applicable and replicable to any area under consideration and should not therefore rely on the motor traffic data of a specific area which may not be available for all locations being considered. A number of tests to determine the effectiveness of boundary weighting were carried out applying different connection and levels associated with the roads at the model boundary as described in Table 11. Tests 1 – 6 used real motor traffic flow figures for boundary weighting and therefore would be more difficult to replicate if real motor traffic flow data is not available. Tests 7 -15 used independent data, and therefore are more replicable if successful. This independent data was either a whole number or was associated to the space around the weighted axial line at the boundary location.

Linear regression analysis was carried out on all data and results are illustrated in Table 11. Four tests recorded no result indicating no relationship (tests 3, 7 and 8). Where results were obtained, these varied from an R² of 0.10 to 0.77. The strongest relationship between real motor traffic flow and integration were obtained when only connection weightings were applied using figures related to the amount of average hourly traffic flow at the boundary location – i.e. tests 1, 4 and 2, all of which had a R² value of greater than 0.7. The results for

tests 11, 12 and 15 which relate the boundary location to the space directly around it demonstrate that a relationship existed between average hourly traffic flow and boundary weighted predicted integration values.

Table 11 - Table of results from 15 boundary weighting tests undertaken on case study area

NR – no result was recorded - integration values were negative.

Test	Connections	Levels	R ² value	Order R ²	Correlation Co-efficient	Order SRCC
No weighting	0	0	0.05			
1	Hourly traffic count figure at each location	None entered	0.77	1	0.875	1
2	Half hourly traffic count at each location	None entered	0.73	3	0.822	3
3	Half hourly traffic count at each location	Half hourly traffic count for each location	NR	-	-	
4	Double hourly traffic count at each location	None entered	0.76	2	0.874	2
5	Five times hourly traffic count at each location	None entered	NR	-	-	
6	10% hourly traffic count at each location	10% hourly traffic count at each location	0.30	8	0.549	8
7	1000 at each location	1000 at each location	NR	-	-	
8	100 at each location	1000 at each location	NR	-	-	
9	1000 at each location	None entered	0.32	7	0.568	7
10	100 at each location	None entered	0.10	10	0.44	10
11*	Radius distance from axial line (1% of number axial lines in whole map)	None entered	0.46	6	0.68	5
12*	Radius distance from axial line (0.5% of number axial lines in whole map)	None entered	0.47	4	0.761	4
13*	Number of axial lines within a 1 mile radius	None entered	0.24	9	0.488	9
14*	Number of axial lines within a 1 mile radius	Number of axial lines within a 1 mile radius	0.12	11	0.426	11

15*	None entered	Number of axial lines within a 1 mile radius	0.47	4	0.628	6
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Test 15 was the only result using the level weighting that had a reasonable R^2 value. All other calculations using levels obtained a very weak result, or no result was recorded. Correlation co-efficient results, as indicated in Table 11, supported the R^2 values calculated with virtually every test positioned in the same order. There is a very small difference with the order of results for test 11 and test 15.

As such, accounting for motor traffic movement across the model boundary did result in a significant improvement in the correlation between motor traffic flow and global integration for the case study area when considered in isolation, and a small improvement when compared to the case study area as part of the whole city integration map. This indicates that the boundary weighting facility did improve the ability of the model to predict motor traffic flow for a small isolated area of a city, for a wide range of roads, although the boundary weighting approaches not based on measured motor traffic counts were not as effective as those that were.

5.4.1.2 Boundary weighting for Cardiff

Using the same approach that had been applied for the case study area as described in Section 4.4.1.3, 12 boundary level tests were undertaken on the whole of Cardiff. Tests 1, 2, 10 and 11 were based on available average hourly traffic count figures, tests 3 and 12 were based on characteristics of the spaces (the number of axial lines contained within the map) and tests 4-9 used independent values for different road types, including core/county roads and M, A and B roads. A summary of the tests and the results obtained is provided in

Table 12.

Table 12 - Results of the boundary weighting tests undertaken on Cardiff

Test	Sample locations	Connections	Levels	R ² value	Order of results	Pearson's Correlation Co-efficient	Order of results
No weightings				0.30	4	0.632	4
1	11 locations at boundary of city	Hourly traffic count	None	0.31	5	0.644	3
2	11 locations at boundary of city	Double hourly traffic count	None	NR	-	-	-
3	11 loop detectors at boundary of city	Global integration value from Cardiff map x 10,000	None	0.29	6	0.623	5
4	10 locations on 6 core 4 county	5000 for core network 2000 for county network	None	0.28	7	0.691	2
5	10 locations on 6 core 4 county	5000 for core 2000 for county	5 for core 2 for county	0.37	1	0.601	6
6	M roads – 3 A roads – 8 B roads – 2	M roads – 5000 A roads – 2000 B roads – 1000	M roads – 5 A roads – 2 B roads – 1	0.32	3	0.582	7
7	10 locations on 6 core 4 county	5000 for core 3000 for county	5 for core 3 for county	0.34	2	0.757	1
8	10 locations on 6 core 4 county	10,000 for core 4,000 for county	5 for core 2 for county	0.32	3	0.491	8
9	10 locations on 6 core 4 county	5,000 for core 2,000 for county	10 for core 4 for county	NR	-	-	-
10	18 locations on M and A roads at the boundary of the city	Hourly traffic count	None	0.17	9	0.279	11
11	18 locations on M and A roads at the boundary of the city	10% of hourly traffic flow	None	0.19	8	0.307	10
12	M roads – 3 NBU – 12 BU – 0	M roads – 1% of axial lines whole city NBU – 0.5% of axial lines within whole city BU – 0.25% of axial lines within whole city	M roads – 0.1% of axial lines whole city NBU – 0.05% of axial lines within whole city BU – 0.025% of axial lines within whole city	0.17	9	0.408	9

It can be seen in

Table 12 that the R^2 values obtained for the boundary weighting tests for the whole of Cardiff ranged from 0.17 to 0.37. This result was not a significant improvement on global integration value calculated for the whole of the city when boundary weightings were not included. Negative results were obtained for tests 2 and 9 as there were too many links through connections and levels.

Correlation co-efficient results ranged from 0.279 – 0.757 with tests 1 and 3-8 demonstrating a strong, positive correlation. The order of results using SRCC varied from the order of R^2 results which is likely to be due to the data being not normally distributed in this test which can affect the regression analysis results. When considering the SRCC results, tests 7, 4 and 1 demonstrated an improved correlation compared to the global integration results.

It is anticipated that weighting designated key routes within the road network using the road weighting facility may improve correlations.

5.4.2 Road weighting

The methodology describing road weighting can be found in Section 4.4.2. These tests were applied to the city wide data only. Tests were undertaken using global integration values with no weighting as well as a selection of potentially replicable boundary weighted results presented above in order to determine the individual effectiveness of the weighting technique, and the overall aggregated improvement when combined with boundary weighting. Data for 148 count locations was available from across the city from loop detectors, automatic traffic count tubes and manual counts. Figure 48 below illustrates the range of roads in each classification that was used within the weightings groups. The road weighting figures that were applied to the different road classifications can be seen in Table 13.

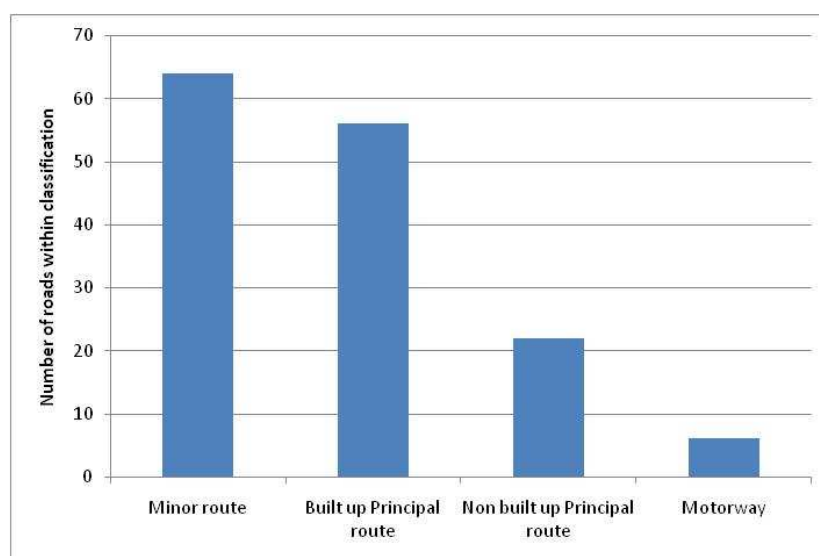


Figure 48 - Graph illustrating the number of roads within each classification within the sample

Table 13 - Road weighting factors applied for tests

Road type	Weighting Values Applied for each Road		
	Weighting Test		
	1	2	3
Motorway	4	5	3
Non built up Principal route >30mph	3	3	2
Built up Principal route ≤ 30mph	2	2	1.5
Minor routes	1	1	1

The results of applying different road weighting factors to different integration maps of Cardiff can be seen in Table 14. The results where no road weighting was applied ranged from R^2 value of 0.06 using only global integration values to 0.37 where the boundary weighting using core and county roads was applied. SRCC also improved significantly from 0.33 with no road

or boundary weighting to 0.72 (strong, positive correlation when boundary weightings were associated with M, A and B roads).

The integration values for all tests where road weighting was incorporated were significantly improved and ranged between an R^2 of 0.6 – 0.72. The largest improvement was seen where road weighting test 2 was applied using global integration values with no boundary weighting, which improved the R^2 value from 0.06 to 0.69. The best overall correlation was found when road weighting test 2 was applied using the integration values calculated when boundary weightings based on County and Core road classification, where an increase of R^2 from 0.37 to 0.72 was seen.

Table 14 - Table illustrating the results of road weighting tests using different integration values for Cardiff

	Integration value	No road weighting		Road weighting test 1		Road weighting test 2		Road weighting test 3	
		R^2	Corr. co-eff	R^2	Corr. co-eff	R^2	Corr. co-eff	R^2	Corr. co-eff
A	Global integration with no boundary weighting	0.06	0.33	0.63	0.82	0.69	0.82	0.68	0.82
B	Integration values calculated from boundary weighting using County and Core roads (test 5 in table 12)	0.37	0.60	0.7	0.85	0.72	0.85	0.68	0.86
C	Integration values calculated from boundary weighting based on M, A and B roads (test 6 in table 12)	0.32	0.72	0.68	0.82	0.68	0.82	0.6	0.83
D	Integration values calculated from boundary weightings based on M, BU and NBU road	0.17	0.53	0.66	0.82	0.70	0.83	0.70	0.83

weightings (test 12 in table 12).									
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The R^2 results were fully supported by correlation co-efficient calculations demonstrating a strong, positive correlation for all road weighting tests. These results indicate that when using road weightings the correlation between spatial analysis calculations and average hourly traffic flow are significantly improved. This analysis was further tested on other cities/regions. As road weighting test 2 had the highest R^2 values throughout the above analysis, the test 2 road ratings (Table 14) were applied in the tests for the additional cities, namely a weighting of 5 for motorways, 3 for non-built up roads, 2 for built-up roads and no weighting for minor roads.

5.5 Test preferred weighting methods on other cities/regions

The above analysis indicated that road weighted tests resulted in a significant improvement in correlation between integration values and motor traffic flow data. Boundary weighted results showed some minor potential for improving model performance whilst being applicable to other study areas, whilst radius integration proved to be largely ineffective at improving model performance. As such, the preferred methodologies of road weighting and boundary weighting have been carried forward to other sample city/regions of Leicester, Leeds and Neath Port Talbot County Borough (NPTCB). The axial maps for each of these cities are presented in Appendix 1.

Figure 49 illustrates the classification of roads used within the analysis. This indicates that there were limitations with the range of data available for each sample area, however, this did typically represent the level of data that would normally be available within a local authority

area and therefore representative of the conditions within which the model would be expected to operate.

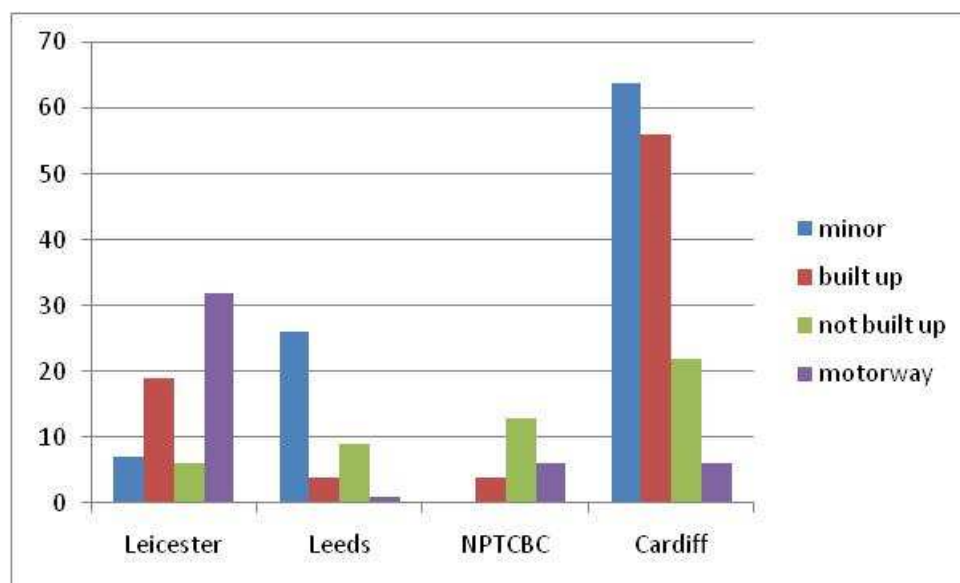


Figure 49 - Classification of roads from cities/regions where motor traffic counts have been obtained

The tests run for each of the three additional city/regions included:

- (i) global integration with no boundary weighting;
- (ii) global integration with road weightings but no boundary weightings;
- (iii) global integration with both boundary weighting (at M/A/B locations) and road weightings (test C in Table 14);
- (iv) global integration with both boundary weighting (% axial lines) and road weightings (test D in Table 14).

In each of the tests for the additional sample cities/regions, road weightings were applied to M, NBU and BU roads as this demonstrated the greatest improvement from no road weightings in the test for Cardiff (test D, Table 14). The results for the additional city/regions can be seen in Table 15 which illustrates that all tests significantly improve both the R^2 and correlation coefficient when compared to the global integration value with no weighting.

Table 15 - Table illustrating the results from different road and boundary weighting tests

City/ region	A Global integration value – no weighting		B Global integration with road weighting – no boundary weighting		C Boundary weighted integration values (M/A/B) with road weighting		D Boundary weighted integration values (% axial lines) with road weighting	
	R ²	Correlati on co- efficient	R ²	Correlati on co- efficient	R ²	Correlati on co- efficient	R ²	Correlati on co- efficient
Cardiff	0.06	0.33	0.69	0.82	0.68	0.82	0.70	0.83
Leicester	0.02	0.16	0.39	0.61	0.22	0.57	0.38	0.61
Leeds	0.01	0.07	0.50	0.44	0.48	0.44	0.48	0.44
NPTCB	0.22	0.53	0.82	0.70	0.86	0.78	0.82	0.70

Results for Cardiff, Leeds and NPTCB indicate that there was little additional improvement between results generated using road weighting only, and those generated using a combination of road weighting and boundary weighting. For Leicester tests B and D provide very similar correlation results but the test for using weighted values on M/A and B roads is not as strong. This may be explained by the higher proportion of motor traffic flow data obtained from motorways for Leicester as illustrated in Figure 49.

Results of the assessment of weighting methods indicate that boundary weighting did improve model performance when isolated areas within a larger axial map were considered. However, boundary weighting did not have a significant impact on the correlation between integration values calculated by the model and measured average hourly traffic flow figures at a city/region scale where no data outside of the city boundary could be utilised (i.e. it is considered as an isolated area). However, when roads were weighted according to national classifications to allow for increased motor traffic flows proportional to the classification of the road, correlations between the integration values and real motor traffic flow figures are

significantly improved across a range of cities/regions with varying road networks and data availability. As such, the application of road weightings to global integration values without incorporating boundary weightings (Test B, Table 14) would be the recommended method to predict motor traffic flow from the spatial analysis model as correlation values calculated are most consistent. The additional data gathering and modelling effort required to also include boundary weighting yielded little additional benefit in terms of further improvement in correlation. The removal of the need to implement boundary weightings reduces the data collection and time resource required by the end user of the model.

5.6 Summary

The results described above demonstrate the use of a spatial analysis model as a means of representing an extensive urban transport network. The use of basic global integration methods within the model was not sufficient to accurately reflect the correlation between modelled integration values and measured motor traffic flows. From the weighting methods investigated, road weighting was found to be the most effective at improving model performance at a city wide / regional scale. The use of boundary weighting did not significantly improve model performance at this scale, however, is likely to be applicable in circumstances where a distinct area within a larger axial map is being considered, as illustrated with the urban case study. In this circumstance, it is likely that data from the surrounding area would be available and therefore implementing boundary weighting would not involve significant additional effort. The model, which is based within a widely available GIS platform, has been shown to produce an output that correlates well with measured motor traffic flow data, which, in the majority of cases is already being collected by local authorities at a level that is sufficient to utilise within the model. As such, it is considered that the initial objectives of the model have been achieved.

Chapter 6: Demonstration of the spatial analysis model for aggregated cycle flow and motor traffic flow

6.1 Introduction

This chapter describes the process involved in demonstrating how the spatial analysis model could be used to quantify cyclist flow rates together with the procedure used to investigate whether the model could quantify how changes to the transport infrastructure influences relative flows of motor traffic and cyclists.

6.2 Demonstration of the spatial analysis model for relative cycle flows

Axial maps describing cycle infrastructure including available roads, off road tracks and access through green spaces for three cycle case study cities have been created to demonstrate that spatial analysis techniques could be applied to cycle networks at a city/ region scale.

The cycle axial maps were initially created for motor traffic (as described in Section 3.2.3) and then modified to represent additional connectivity for cyclists. Modifications to the motor traffic maps were made to incorporate all additional possible routes available to cyclists. Modifications to each map included the removal of motorways (illegal access for cyclists), linking up dead ends to motor traffic where cycles are able to pass through (but are inaccessible to cars), inclusion of motor traffic free streets, off road cycle paths and routes crossing green spaces. Cycle maps for Bristol, Cardiff and York were used to ensure that the axial maps were presented as accurately as possible. The initial axial map was colour coded to represent different cycle provision in each of the cities and the number of axial lines in the motor traffic and cycle maps were compared to evaluate the additional network available to cyclists.

Figure 50 illustrates case study 1 – urban area (Canton and Pontcanna) which is located in Cardiff. This provides some examples of points where connections are available for cyclists

but not available for motor traffic. Modifications such as these were made to the motor traffic map across the entire axial map. This demonstrated that it is possible to represent cycle connectivity using spatial analysis techniques. Spatial integration was then run in the same way as for motor traffic flow.



Figure 50 - Case study 1 - urban area. Example of connections available to cyclists that are inaccessible to motor traffic

Characteristics of the cycle network in the case study 1 – urban area were then obtained from the Cardiff County Council cycling and walking map to investigate the potential to ‘weight’ routes with cycle facilities (Cardiff County Council, 2013). No off-road routes were located within the area and segregated on-road routes were not indicated on the map, although both sign-posted cycle routes and advisory routes were displayed. To demonstrate the ability to

weight cycle routes both sign-posted cycle routes, and advisory routes were given a weak weighting of 2, assuming that these routes were considered slightly more attractive to cyclists than a typical on-road route. Integration was re-run including these weighting factors for cyclists. The results are presented in Chapter 7.

6.3 Application of spatial analysis model to demonstrate modifications to motor traffic and cyclist infrastructure

In order to demonstrate how the results of the research could be used to investigate interrelationships between the road network and cycling, tests were run to illustrate how the spatial analysis map can be used to represent the impact of:

1. The closure of a road to motor traffic on relative traffic flow in the surrounding area and the associated positive weighting of the same road for cycle traffic due to an increase in attractiveness due to no motor traffic being present;
2. The linking of two non-linked spaces for cyclists to increase accessibility and connectivity in a space.

Case study 1 – urban area was used to demonstrate the potential for the spatial analysis model to investigate the impact of infrastructure changes both to the motor traffic and cycle network. Spatial integration calculations were used to demonstrate the change in relative flow on different routes when a change is made to the network by reducing the availability of the road network to cars - blocking a road off to motor traffic - and increasing weighting for cyclists due to a lack of motor traffic on the same route. Increasing connectivity for cyclists by adding in additional routes was also investigated.

The creation of the test axial map and investigations were undertaken in a number of stages:

- 1 The road map for the case study 1 – ‘urban area’ was initialised and integration values were calculated (as described in Section 3.2.3);
- 2 Any motorways, non-built up roads, built up roads (as described in Section 4.4.1.1) were weighted using the most successful methodology for motor traffic as described in Section 4.5. Only built up (M, A or B) roads were located within the case study 1 area due to its urban situation, these are illustrated in Figure 51. A weighting factor of 2 was used to weight these. Spatial integration was rerun with the weighting factors included.

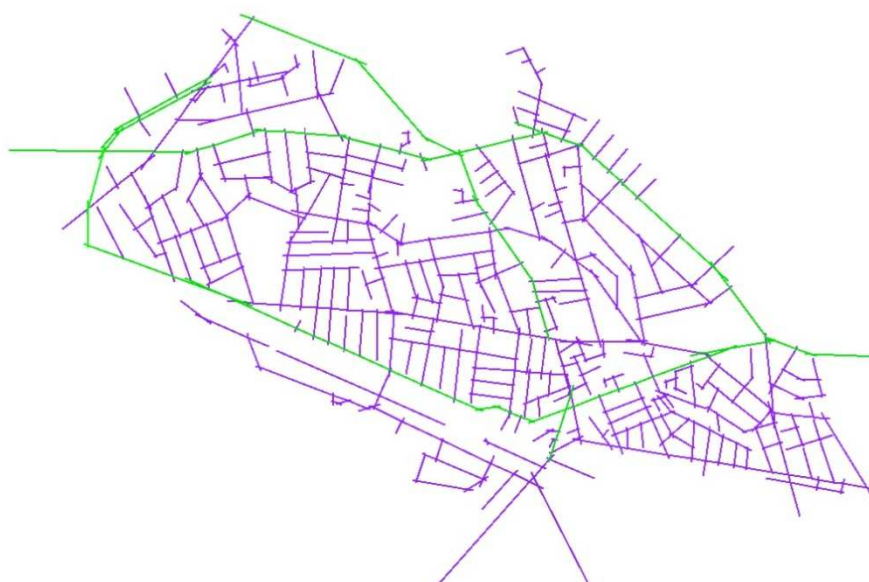


Figure 51 - Case study 1 - urban area. Built up roads to be weighted are highlighted

- 3 A road currently accessible to motor traffic was removed from the motor traffic axial map to represent closure of the road to motor traffic. The road removed is illustrated on Figure 52. Spatial integration was re-run for the motor traffic axial map to illustrate the impact on integration values.
- 4 The axial map representing the cycle network, which includes modifications made according to accessibility for cyclists, was initialised and spatial integration was run to produce global integration calculations for each axial line.

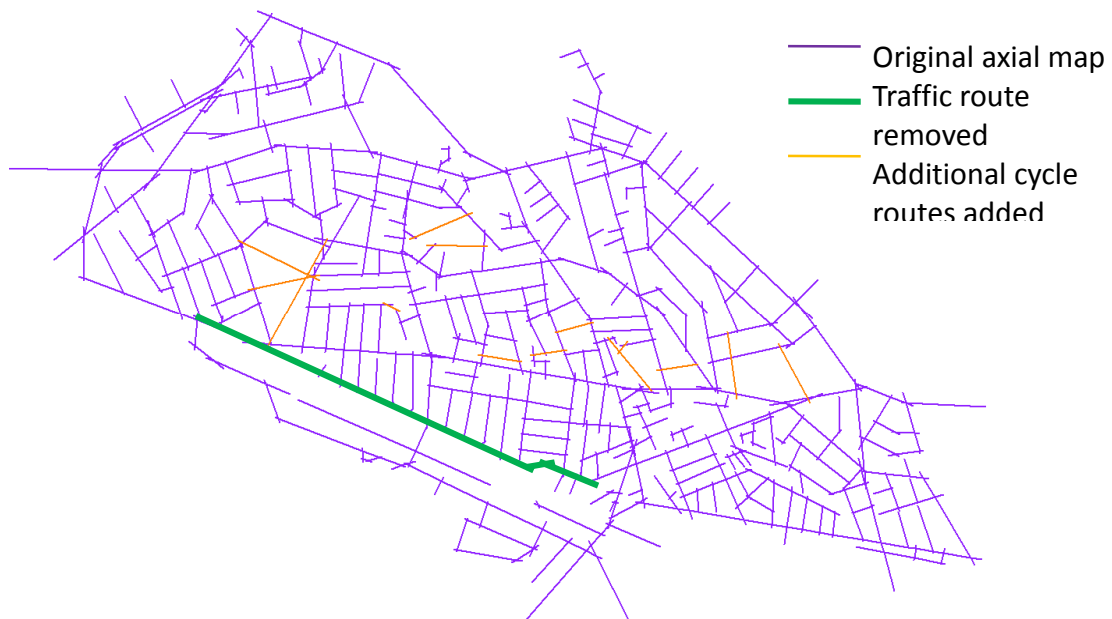


Figure 52 - Case study 1 - urban area. Motor traffic accessible route to be removed and cyclist routes to be added

5 a) weightings were added to the axial lines for the motor traffic route that was taken out from the motor traffic map (highlighted in green in Figure 52) within the cycle map. The assumption is that by having no motor traffic passing along it, it will become more favourable to cyclists (Wardman, 2007) (as presented in Section 2.8).

b) additional routes available to cyclists were incorporated to provide a more connected network. The additional routes are highlighted in orange in Figure 52 and were identified as potential locations to open up the cycle network providing more connected routes. Minor modifications to infrastructure within the network to allow these connectivity changes to take place include:

- Allowing longer opening times to urban parks throughout the year to allow commuters to pass through between extended working hours particularly during the winter period. Strategically located lighting would reduce security issues;
- Utilising rear lane access, particularly common in dense urban areas, by providing cycle friendly gateways from these lanes to adjacent roads that are currently

inaccessible. Figure 53 indicates that by removing a small fence and providing a footpath between adjacent streets, connectivity can be increased. The orange line indicates the new connection between two previously unconnected roads.

- Allow restricted movement across public owned property such as schools and hospital to increase connectivity.



Figure 53 - Urban location demonstrating potential for increased connectivity for cyclists

Visual comparisons were made between the axial maps as described above to highlight the impact that the modifications have on the relative flow patterns predicted by the model.

6.4 Summary

Axial maps describing cycle infrastructure including available roads, off road tracks and access through green spaces have been created for three case study cities have been created to demonstrate that spatial analysis techniques can be used to represent connectivity on an urban scale. A method of weighting has been tested using cycle facility data from the local authority. Tests have been run to illustrate how spatial analysis can be used to represent the impact of road closures to motor traffic on cyclists and improving connectivity for cyclists by linking non-linked spaces.

Chapter 7: Results from the demonstration of the spatial analysis model for aggregated cycle flow and motor traffic flow

7.1 Introduction

This chapter demonstrates that the spatial analysis model techniques developed can, in principle, be used to represent relative cycle flows across urban areas using the process described in Chapter 6. Results from the implementation of spatial analysis of relative flow of cyclists are presented as a series of axial maps. The impact of improved accessibility for cyclists and reduced accessibility for motorists are presented to demonstrate the potential of the model to illustrate change in flow of cycle traffic relative to motor traffic.

7.2 Results from the demonstration of the spatial analysis model of relative cycle flow

Axial maps of the cycle networks within the three cities used for the cycle analysis were created – Figure 54 – Cardiff, Figure 55 – Bristol and Figure 56 – York. These figures also illustrate individual local authority classification of cycle routes which are represented by different coloured axial lines, presented in the associated keys. Each map was created initially for motor traffic and then modified to represent connectivity for cyclists. Examples of modifications to each map included the removal of motorways, linking up routes that were dead ends to vehicular traffic but where cycles were able to pass through, incorporating off road cycle paths and routes crossing green spaces.

The number of axial lines within the motor traffic and cycling axial maps for the three cities used for the cycle studies are shown in Table 16. This indicates that the cycling network includes 30% more axial lines within the axial map for each city compared to the motor traffic network demonstrating the additional level of connectivity that cyclists could, in theory, utilise. It also serves to illustrate the additional modelling effort that is required to map cycling

networks, or to modify existing models to accommodate cycling all potential cycling routes. Axial maps with integration values illustrated can be seen in Appendix 2.

Table 16 - Illustration of the range of axial lines in the motor traffic and cycling axial maps created

City	Axial lines in motor traffic map	Axial lines in cycling map	Difference	% increase
Cardiff	7,731	9,882	2,151	28
Bristol	6,961	9,306	2,345	33
York	5,378	7,092	1,714	32

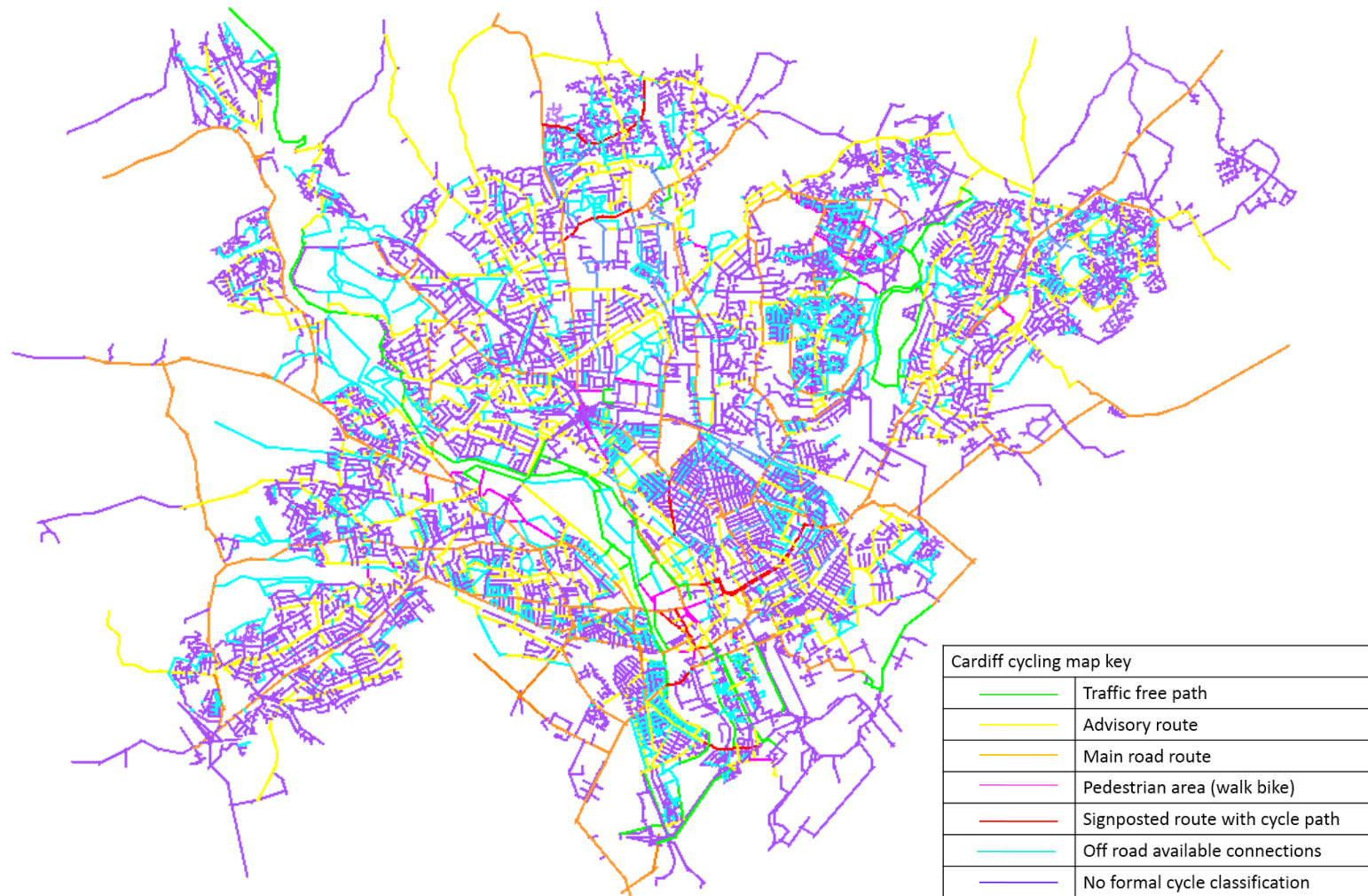


Figure 54 - Cycle axial map for Cardiff including cycle facilities



Figure 55 - Cycle axial map for Bristol including cycle facilities

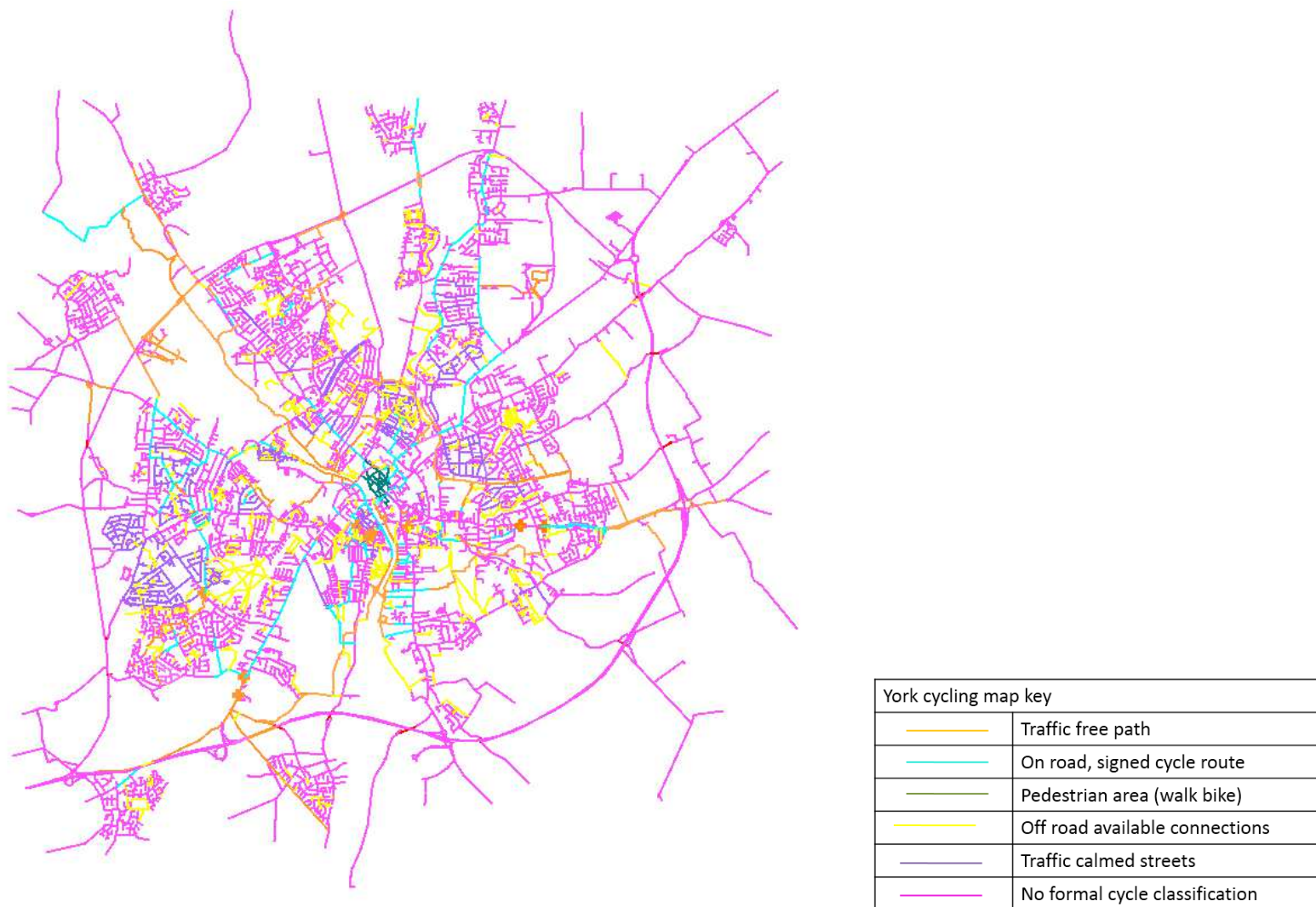


Figure 56 - Cycle axial map for York including cycle facilities

In order to produce an output that is potentially useful for identifying routes that are more likely to be used by cyclists, the most successful weighting methodology from the motor traffic modelling work, as presented in Chapter 5, was applied to cycle routes. In the same way as road weightings were applied, a hierarchy of cycle routes, as discussed in Section 2.7, could be applied as a means of weighting routes that are more favoured by cyclists (Wardman, 2007):

- segregated off-road;
- segregated on-road;
- non-segregated on-road;
- roads with no facilities;

The basic global integration map for the case study 1 - urban area (Canton and Pontcanna) for average hourly motor traffic flow when isolated from the city wide map is illustrated in Figure 57. This illustrates that as expected, that the most integrated roads were located towards the centre of the map with the outlying, less integrated roads towards the edge, as roads were not connected across the boundary and were therefore not configured to any other lines.



Figure 57 - Case study 1 – urban area motor traffic flow global integration

To demonstrate the potential to include route weightings to assist with predicting cycle flows for every route within a network, weightings were applied to the case study 1 – urban area cycle network integration map. Both signposted cycle routes and advisory routes have been given a weighting of 2 based on the assumption that these routes were considered as ‘non-segregated on-road’ based on the hierarchy presented above and were more attractive to cyclists than a route with no features. Integration was re-run for the cycling axial map using these weighting factors, the results of which are shown in Figure 58.

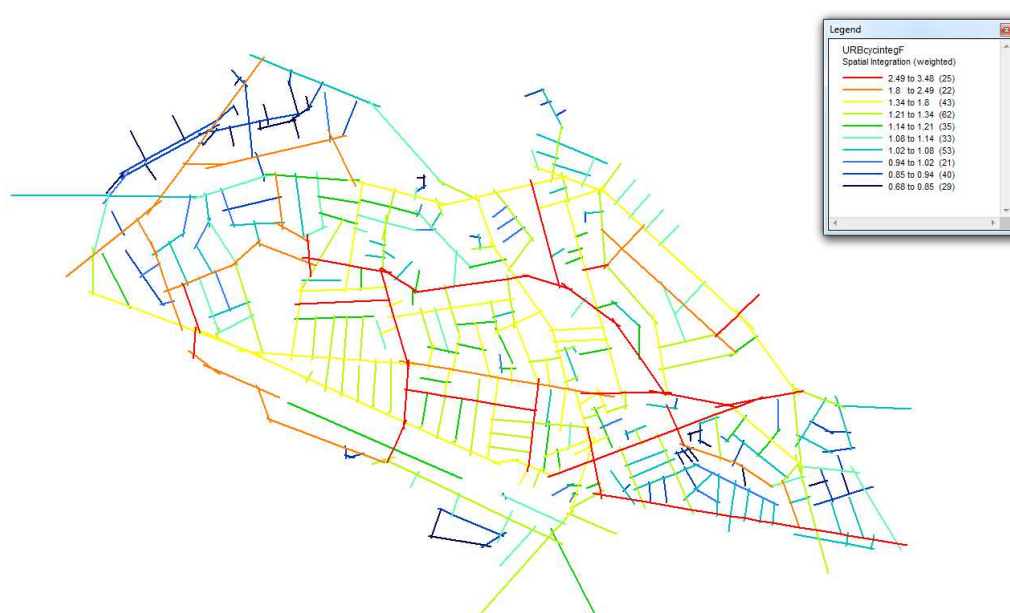


Figure 58 - Case study 1 – urban area cycle network global integration with route weightings applied

Figure 58 demonstrates that space analysis modelling can be used to represent an urban cycle network and that weighting methodologies that were successful with regard to motor traffic flows can also be applied to potentially represent preferential cycle flows along key routes. The model therefore provides the potential to investigate the effectiveness of cycle network provisions which would shift routes up the cycle route hierarchy on a city wide or sub-area basis with relatively little time and resource input.

Unfortunately, data relating to cyclist flow rates was not collected by the local authorities involved in the study, and the expense and time required to gather such data meant that its collection was outside the scope of this thesis. The collection of reliable and accurate cyclist flow data is difficult to achieve (as discussed in Section 2.12). Without such data it is not possible to validate the cycle model in the same way that the motor traffic model has been validated.

7.3 Results from the application of the spatial analysis model to demonstrate modifications to motor traffic and cyclist infrastructure

This section of the thesis demonstrates the potential for spatial analysis modelling to represent the impact of infrastructure changes both to the motor traffic and cycle network and how changes to one network can impact on accessibility, and therefore flow rates, within the other network. Case study 1 – urban area (Canton and Pontcanna) has been used to demonstrate how alterations to infrastructure can influence relative flows on surrounding roads/routes.

By adding or removing connections within an axial map, changes in relative flow in surrounding areas were investigated. Results were represented by changes to the integration values of surrounding axial lines. This enabled the investigation of allowing or denying vehicular access on particular routes, where spaces can be connected or disconnected by simply adding or removing lines within the axial map.

The basic global integration map for the case study 1 - urban area for average hourly motor traffic flow when isolated from the city wide map is illustrated in Figure 57. Figure 59 shows the global integration using the road weighting method described in Section 5.5. This indicates that built-up and non-built-up roads within the case study area were now considered more

integrated than minor roads. As previously presented, strong, positive correlations between average hourly motor traffic flow and road weighted integration values have been confirmed for motor traffic.



Figure 59 - Case study 1 – urban area motor traffic flow global integration with road weightings



Figure 60 - Case study 1 – urban area motor traffic flow global integration with selected road removed to demonstrate the change in relative flow patterns as a result of motor traffic infrastructure changes

As presented in Section 6.2, it is possible to simulate the modification of the motor traffic network such that vehicle access is denied along a previously available route simply by removing the appropriate axial lines from the axial map. Figure 60 presents a revised weighted integration map for the case study area with one built up road removed from the axial map (comprising three axial lines). It can be seen that the relative integration value of the straighter east to west route to the north of the removed route together with roads adjacent to that route become relatively more integrated compared to the other axial lines (indicated as red or orange in the axial map) and therefore based on the results in Chapter 5 are likely to have increased levels of motor traffic flow as a result of the road closure.

The integration map for cycling for the same case study area is presented in Figure 61 when treated in isolation. An additional 40 axial lines were included within this axial map compared to the motor traffic map, reflecting routes that are available to cyclists but which are unavailable to motor traffic.



Figure 61 - Case study 1 – urban area cycle network global integration

As with Figure 57, the more integrated routes are located around the centre of the map with less integrated routes around the periphery.

Spatial analysis was rerun on the cycling map with a weighting factor of 5 being applied to the route that has had motor traffic removed as indicated in Figure 60 in order to assess the impact that this road closure might have on cycle flows (Figure 62). This demonstrates that there would be a significant shift in cycle flows to the motor traffic free route.



Figure 62 - Case study 1 – urban area cycle network global integration with weighting factor applied to motor traffic free route

Further investigations were undertaken to simulate the creation of additional cycle network infrastructure. Additional cycle routes were incorporated into the axial map by adding new axial lines, the effect of which was to increase the connectivity of spaces for cyclists. The locations of these additional routes are indicated in Figure 52 (Section 6.2). The resulting integration map is presented in Figure 63. This map indicates the shift in cycle movements as a result of the improved connectivity with a slight shift of the centre (or the most connected area) of the integration map, and as a result a change in the relative integration values of the routes adjacent to the new routes.



Figure 63 - Case study 1 – urban area cycle network including additional routes (global integration with route weightings)

7.4 Summary

The axial maps for the cycle network are presented for each of the three cities. The weighting methodology from modelling motor traffic was applied to routes likely to be more favourable to cyclists. As discussed previously, the results from the work illustrated above could not be validated as detailed cyclist data was not available to correlate with integration figures calculated. The model was also used to demonstrate how modifications to motor traffic and cyclist infrastructure could be represented, by denying vehicle access and increasing weighting factors for cyclists along the same route. The research demonstrates that the spatial analysis techniques developed and applied can be used to produce output that would potential be useful when modifying urban infrastructure to attempt to provide more connected routes for cyclists.

Chapter 8: Collection and analysis of individual cyclist movement and behavioural data

8.1 Introduction

Previously in this thesis spatial analysis mapping techniques have been applied to find out whether the model could be used to predict aggregate journeys of motor traffic and cyclist traffic. This chapter takes an individual cyclist based approach to identify whether cyclists use the most direct/connected route available, as predicted by the spatial model, or whether the preference is to deviate to use routes with cycling facilities or other favourable characteristics, even if they have to increase the length of their journey. Two approaches have been taken to investigate individual cyclist behaviour, spatial analysis modelling and the administration and analysis of a questionnaire.

8.2 Spatial analysis modelling to predict individual cyclist routes

Spatial analysis procedures have been developed to predict the most direct journey from one individual location to another (as part of the FIT funded project (Section 3.2.1)). This allows the most direct route that can be taken to travel from one location to another i.e. the route that requires the fewest changes in direction directly from one specific point to another, to be predicted. Comparisons were made between the actual journey taken from home to work as indicated by respondents on a local map included within a questionnaire (Appendix 3) and the model predicted most direct journey. The route to work was selected for analysis as the journey is generally routinely made, carefully planned, involves relatively short distances travelled by a generally physically able population group and is therefore an ideal focus for modal shift from the car to bicycle. This has been discussed in detail in Section 2.7.

The analysis was intended to investigate whether cyclists do take the most direct route to work regardless of facilities available or problems encountered on route. Where the route taken

deviates from the most direct route, further investigations were made from the map and from the responses to the questionnaire to identify what route characteristics were likely to deter from or attract to the most direct route. If a strong relationship can be identified between the predicted routes and actual routes as indicated by cyclists, routes typically taken by cyclists on their journey to work can be identified which will aid the channelling of resources to routes favoured by cyclists. Attractors or deterrents can then be considered when designing new routes within a city or to improve existing routes.

Within the questionnaire administered in the three cities involved in the cycle study (presented in Appendix 3, discussed in section 8.3), respondents were asked to draw onto a map the usual route taken from home to work as accurately as possible using a coloured pen. For each of the three cities, 100 questionnaires (n=300) were randomly selected using a computer based random number generator. For each of these, the actual route to work was mapped into GIS MapInfo using the base cycling axial map as described in section 3.2.3.

The spatial analysis mapping software was then used to predict the most direct route that could be taken from each individual starting point - origin (home) to the end point – destination (workplace). Information for each of the 300 reported routes was then recorded to enhance analysis, including:

- questionnaire code;
- whether the cyclist perceived that they took the shortest route;
- whether they cycled every day, frequently or occasionally;
- the total distance for predicted and actual routes;
- the length of route where actual and predicted routes are the same;
- the percentage of the separate predicted and actual journeys that take place on:
 - off road route cycle facility;

- on road cycle facility;
 - traffic calmed, advisory routes;
 - roads with no facilities;
- the proportion of the journey where the routes are the same.

A visual comparison and basic quantitative analysis was then made between the actual route taken by a cyclist, as drawn within the questionnaire, and the most direct route predicted by the model. The model identified the route that is the path of least complexity. This enabled identification of:

- whether cyclists actually do take the most direct route to work (with the fewest changes of direction);
- whether they perceive that they take the shortest route;
- how much they deviate from the most direct route;
- if they do deviate significantly from the most direct route, whether they choose to cycle on a route that has better cycling facilities/less motor traffic/other characteristics? Does the route choice correspond to the conscious questionnaire response?

8.3 Collection and analysis of individual cyclist behavioural data

This element of the investigation involved the preparation and distribution of a questionnaire and analysis of results to investigate the influence of cyclist behaviour on route choice, the decisions behind undertaking a journey to work by bicycle, the frequency and occasions that a bicycle is used and the reasons for choosing the route taken. The aim was to identify commonalities in behaviour across cities with regard to the extent to which journeys are undertaken by bicycle and the factors behind the choice of mode and route taken. A better understanding of these factors will influence the overall positioning of cycling infrastructure within cities and can be utilised with the modelling data obtained from previous work.

The questionnaire was also used to establish ‘actual’ cycle journeys to identify routes that are being used by cyclists (as described in Section 8.1). Information regarding the extent to which journeys were undertaken, by cycle or other modes, by people who do cycle to work at least occasionally, and the factors behind the choice of mode were collated. Other information collected included purpose of trip, location of start and finish points, distance travelled, route adopted, means of transport, the time at which it was made and the frequency in which it was carried out.

8.3.1 Sample identification and questionnaire distribution

As the study aimed to question people who do cycle to work, a methodology was required to target this population group. A number of different ways in which the questionnaire could be promoted and distributed were considered including articles in local press and cycle newsletters requesting a response, distribution by hand at the place of work and distribution by post to all households within selected areas of each of the cities. It was decided that the most effective way to distribute the questionnaires was at the workplace and to question cyclists only, whether they cycle every day or a few days a year. In order for non-cyclist data to be of value, the degree of potential modal shift would have to be analysed which would require additional questions and detailed analysis and would change the emphasis of the research of this thesis.

The study aimed to obtain information from those who have some experience of cycling to work in order to gain an objective assessment of cycling facilities and issues associated with cycling. By only including cyclists within the survey, analysis focused on the characteristics that deter occasional cyclists from cycling more often, and also identify possible variations in

route choice between occasional cyclists compared to more frequent cyclists. This method directly targets those who are in employment rather than the general population, which removes the expense of postage to those who do not cycle and/or do not cycle to work.

In each of the case study cities a number of organisations who had set up either a Bicycle User Group (BUG), a Green Travel Plan or were known to be promoting cycling in the workplace were identified. A list of these potential participant organisations was collated and approached by telephone and letter to request involvement in the study. Other general cycling groups were also approached including members of the 'Green Commuter club' in Bristol who were involved in developing personal travel plans. Distribution was not limited to these organisations, and 'word of mouth' between cyclists further increased the sample. The questionnaire included a space for respondent contact details to be collected to enable identification of source and end point of journey including telephone number and address.

Representatives from each potential participant organisation were contacted via telephone to confirm whether the organisation agreed to take part and to identify the name of an appropriate person to send information. On confirmation of support, a letter documenting how the organisation could help together with a poster to promote the questionnaire to colleagues and members of the public who may visit the organisation was sent. Recommendations included that, where possible, an e-mail address should be sent to colleagues to publicise the questionnaire giving instructions on where a copy could be obtained. It was suggested that questionnaires and a poster be left where people congregate or pass through every day, such as reception desk or canteen. Placing the questionnaires in a bicycle storage facility was also recommended if secure and waterproof.

The questionnaires were distributed by hand to each company representative and other individuals during National Bike Week. At this time publicity on the benefits of cycling was in high profile in the national press and it was also when people who were occasional cyclists were more likely to be using their bicycles to get to work during the summer months. Additional questionnaires were provided on request from individuals/organisations during the summer period. Questionnaires were either collected by the representative for each company and returned together, or were returned individually by the respondent by post to a freepost address.

8.3.2 Questionnaire Design and Collation

The questionnaire was developed from a review of previous questionnaire surveys (Tolley and Turton, 1995, Hopkinson and Wardman, 1996; Gardner, 1998; Ortúzar, 2000) together with previous experience of questionnaire design (Housing and Neighbour and Health research project funded by the MRC, Thomas H et al, 2007). The questionnaire was piloted on WSA students and staff. Questionnaires distributed in each city were printed on A3 folded booklet format and were printed on different coloured paper to assist with data collation and entry and all questionnaires were coded on receipt. The self-administered eight page questionnaire comprised of an explanation of the survey together with 24 main questions covering the subjects of:

- cyclist characteristics;
- frequency of cycling;
- distance travelled;
- route choice;
- factors that attract/deter people to cycle;

- a local OS map for the respondent to draw on the route of their journey to work together with a request to identify locations where cyclists felt were accident ‘hotspots’.

A prize of a ‘Selle Royal’ gel saddle was provided by Dawes Cycles as an incentive to complete the questionnaire. A copy of the questionnaire can be found in Appendix 3.

For many of the questions a four point likert scale was used, for example, respondents were asked whether certain factors deter them from cycling ‘A great extent’, ‘moderate’ ‘very little’ or ‘not at all’. For other questions, pre-specified categories were provided and more than one response could be selected together with an open category box for additional responses not included within the pre-specified list.

8.3.3 Data entry and analysis

Questionnaire responses were entered into a MS Excel table. Different worksheets were used for questionnaires returned from Cardiff, Bristol and York. Data was aggregated to enable combined results to be analysed as well as to allow analysis on individual cities. Each questionnaire was coded depending on source city:

- Bristol (green paper) – 1000 to 1999;
- Cardiff (gold paper) – 2000 to 2999;
- York (blue paper) – 3000 to 3999.

Where data was missing a dummy code of –999 was used. Where data was incorrectly entered such as two boxes being ticked where there should only be one -888 was used. An A3 map of the relevant city was included within the centre of the questionnaire, reproduced with the permission of the Ordnance Survey. This enabled the respondent to mark their journey to work. A box for the respondents name, address, email and employer was included on the back

of the questionnaire. Respondents were asked to include this information if they did not mind being asked further questions if necessary, or if they would like to enter the prize draw to win a new saddle. Instructions for completion of questionnaire were included. Data was analysed using SPSS version 11. Descriptive statistics were used to describe the characteristics of the respondents including characteristics of the sample and the route they take, perceptions towards cycling and description of the journey to work. The results from the questionnaire were analysed:

- as a total sample;
- on an individual city basis – for Bristol, Cardiff and York;
- on the basis of cycle journey frequency – every day - cycle everyday of the year, frequent – cycle a few days a week, occasional – cycle once a week or less.

Further analysis was undertaken using Categorical Regression Analysis (CATREG) to identify the dominant characteristics in the decision to undertake a journey by cycle. This statistical analysis technique, developed at the Leiden University (Meulmen, 1998), is used to identify the relative contribution of multiple variables using binary variables. The analysis does not require numerical variables but can accommodate binary outcome (yes/no) variables, which were the format of some of the responses in the questionnaire, and can work with relatively small sample sizes and mixtures of data types. The analysis was undertaken using a version of CATREG available within SPSS for Windows version 11.

The dependent variable used was the ‘frequency’ classification. Three groups of cyclists were identified according to how often they cycle to work, as reported in the questionnaire; (i) every day - cycle everyday of the year; (ii) frequent – cycle a few days a week; (iii) occasional – cycle once a week or less. These three groups were analysed to assess whether each group was influenced by different factors. These classifications were based on McClintock’s (2002)

suggestion that there are three basic categories of cyclist: the fast commuter who will tend to ride on roads, the utility cyclist and the vulnerable and less confident cyclist.

The results from this analysis were used to identify factors that would maintain the levels of cycling by those in the everyday group, and to encourage those in the frequent or occasional groups to cycle more often. 65 questions from the questionnaire were able to be used as independent variables in the analysis. These questions were selected as they describe the characteristics of the cyclist or journey that may influence the frequency of cycling. These are presented in Table 10.

Table 10–Responses used in CATREG analysis

Independent variables
Age
average journey time
better facilities at work - encourage cycle more
bike theft – risk
business travel - extent deters cycling
condition of cycle route – risk
condition of road surface- risk
conflict with pedestrians – risk
contact with nature - decision to cycle
cost saving - decision to cycle
danger from traffic - deter from cycling
dark mornings/evenings - extent deters cycling
decrease in road congestion - encourage cycle more
difficult junctions – risk
distance from door to door
Do you take the shortest route
encouragement from employer - decision to cycle
environmental benefit - decision to cycle
health/fitness - decision to cycle
hills - deter from cycling
How dangerous are cars/vans when you cycle to work
How dangerous are motor cycles when you cycle to work
How dangerous are other cyclists when you cycle to work
How dangerous are pedestrians when you cycle to work
How dangerous is public transport when you cycle to work
illness from pollution – risk
inflexible working hours - deter from cycling
influence of cycle lane provision
influence of exposure to traffic
influence of gradient
journey length - deter from cycling
lack of dedicated cycle lanes - deter from cycling

more expensive parking - encourage cycle more
more expensive fuel - encourage cycle more
motor traffic – risk
multipurpose trip - extent deters cycling
need to carry bag/equip - deter from cycling
need to carry bag/equipment - extent deters cycling
need to combine journeys - deter from cycling
need to dress formally - deter from cycling
night time lighting on off road cycle routes- risk
night time lighting on roads- risk
no alternative - decision to cycle
other cyclists – risk
other mode journey time
parked cars – risk
personal attack- risk
personal safety - deter from cycling
poor physical fitness - deter from cycling
rating of public transport
relaxing experience - decision to cycle
road pricing - encourage cycle more
safer on/off road - encourage cycle more
sense of independence - decision to cycle
Sex
shorter route - decision to cycle
support from employer - deter from cycling
time cycling on busy road with no cycling provision
time cycling on cycle/bus lane on busy road
time cycling on cycle/pedestrian route (no motor motor traffic)
time cycling on quiet road
time saving - decision to cycle
varied route - decision to cycle
weather - deter from cycling
weather conditions - extent deters cycling
Dependent Variable: Frequency of cycling during winter and summer

CATREG was used to identify the difference between each group rather than the absolute characteristics that act as a positive or negative factor for all cyclists which were analysed within the descriptive statistics. The most dominant characteristics of a cycle journey were identified for each group, highlighting the characteristics that could be modified in an attempt to encourage greater cycling frequency. Categorical regression analysis was used to identify factors within different cyclist groups in the decision to cycle from the various characteristics presented. These are likely to vary between groups due to the variations in attitude to cycling.

8.4 Summary

Techniques for utilising spatial analysis to predict the route of individual journeys are presented which are used to identify whether cyclists use the most direct route available, as predicted by the model, or whether the preference is to deviate to use routes with cycling facilities or other favourable characteristics. The process involved in the preparation and distribution of a questionnaire to investigate the influence of cyclist behaviour on route choice, the decisions behind undertaking a journey to work by bicycle, the frequency and occasions that a bicycle is used and the reasons for choosing the route taken is described. Results are presented in Chapter 9.

Chapter 9: Results from the collection and analysis of individual cyclist movement and behavioural data

9.1 Introduction

This section of this thesis presents the results that illustrate whether the spatial analysis model could be used to predict individual routes taken by cyclists who believed they chose to take the shortest route when they cycled to work. This combines modelling work and the results of the questionnaire. Modelling was undertaken to identify whether accurate predictions of the route that an individual cyclist chooses at a fine level can be made. This would assist with the design of an effective cycle network, despite the unavailability of wide scale cycle flow data, as individual routes could be accumulated to predict mass cycle movements from source to destination therefore identifying routes likely to be commonly used. A comparison was made between the most direct route predicted by the spatial analysis model with the actual route taken as identified by the cyclist during a questionnaire survey, as described in Section 8.0. Actual cycle routes taken by cyclists were also analysed to identify the nature of the route chosen.

The results of a questionnaire survey that was undertaken within the three case study cities of Cardiff, Bristol and York were used to investigate the characteristics of cyclists, choices that are made by cyclists when considering route to work, and factors that affect whether to cycle at all, therefore providing an insight into cyclist behaviour. A total of 2,932 'Do you cycle to work?' questionnaires were distributed throughout the three case study cities as described in Section 8. 990 questionnaires were distributed in Bristol, 975 in Cardiff and 967 in York. Questionnaires were returned from 152 different companies - 61 organisations in Bristol, 45 in Cardiff and 46 in York. 1,245 questionnaires were returned in total with return rates being; Bristol 40% (n=390), Cardiff 52% (n=514) and York 35% (n=341). Therefore the overall response rate for the three cities was 42%.

9.2 Results from spatial analysis modelling when used to predict individual cyclist routes

As the journey to work is an essential and routine journey it is assumed that most cyclists would ideally cycle along the most direct or shortest route if favourable conditions prevail. This assumption is supported by research by Lee and Moudon, (2008); Caulfield et al. (2007); Barton, (2007); CROW, (2007) together with results from a questionnaire where 70% of respondents believed they took the shortest route to work.

The start and end points of all journeys for a random sample of 100 respondents from each city were mapped, together with all perceived dangerous junctions and cycle facilities as described in Section 8.2. The actual route/stated preferred route taken between these points by the cyclist, as identified from the questionnaire survey, together with the most direct route calculated by the space analysis model, was also plotted. Figure 64 and Figure 65 present the stated preferred route as taken by sample respondents within the survey (red) and the most direct route as predicted by the model (purple). In Figure 64, the route is accurately predicted by the model.



Figure 64 – Illustration of stated preference route taken by sample cyclist and route predicted by model – accurately predicted by model

Figure 65 illustrates partial prediction by the model. The route predicted by the model follows the on-road option which comprises straighter route, however, the route identified by the respondent within the questionnaire takes an off-road cycle route, which would be considered less direct by the model due to the larger number of axial lines included within this option.

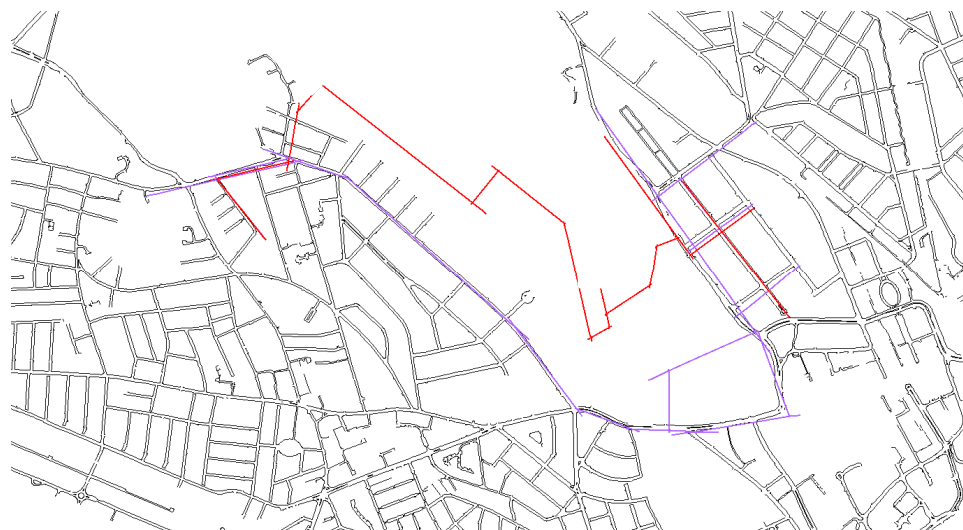


Figure 65 - Illustration of stated preference route taken by sample cyclist and route predicted by model – partial prediction by model

The results when comparing the shortest route predicted by the model with the actual journey of all sample respondent for each city who believed they took the shortest route are shown in Table 17. This illustrates that by using the spatial analysis model an average of 25% of journeys, where cyclists perceive they took the shortest route (70% of sample), can be predicted completely, i.e. from start point to end point, ranging from 19% in Bristol to 29% in York. These cyclists chose to take the most direct route from home to work regardless of whether there were cycle facilities available. Over one third of journeys (35%) were predicted to an accuracy of 75% (Table 17) within each city and over half the journeys were predicted with 50% accuracy.

Table 17 - Comparison of percentage of the journeys predicted by the model for each city

	100% journey predicted by model	75% of journey predicted by model	50% of journey predicted by model
Bristol	19%	33%	54%
Cardiff	26%	34%	52%
York	29%	40%	53%

These results indicate that although cyclists believe they chose the most direct route to work, predictions by the model illustrate that this was not the case. This supports previous work (Tilahun, 2007; Hopkinson, 1996) that cyclists are prepared to alter their route to cycle on a more ‘attractive’ route. The fact that cyclists believed that they were taking the most direct route suggests that this modification of behaviour might be at least partially sub-conscious, or that they may not even consider the actual most direct route as a viable option.

When the detail of the routes chosen were visually assessed using GIS it was seen that the journeys taken along off-road cycle facilities were predicted less well in all three cities, as illustrated in Figure 65. One explanation for this is that off-road cycle facilities tend to follow routes that are less direct often involving many small changes in direction. The spatial analysis model demonstrated a preference for routes that were better linked to the network as a whole and followed the line of sight, which tended to be roads.

For the city of York, predictions indicated that many journeys should take place along the ring road as this route was more direct and it included fewer changes in direction. Despite cycle facilities being situated in many places on this route and the actual length of the journey not being substantially longer than alternatives, the perceived length of the route was considered

longer as an initial detour away from the destination (i.e. the city centre) was required in many cases.

An assessment was made of the difference between the nature of the cycle facilities provided on routes predicted by the model and those on the actual route taken by cyclists. Table 18 below illustrates the average percentage of the route that took place on different types of cycle routes for predicted and actual journeys. Across the three cities almost half (48%) of both actual and predicted journeys took place on routes where no cycling facilities were provided.

Table 18 - Comparison of the actual and predicted routes on different route types

City		Off-road paths	On-road lane	Traffic calmed/ advisory	No facilities
Bristol	Actual	12%	13%	23%	52%
	Predicted	10%	10%	13%	67%
	Difference	2%	3%	10%	-15%
Cardiff	Actual	16%	11%	28%	45%
	Predicted	7%	6%	21%	66%
	Difference	9%	5%	7%	-21%
York	Actual	18%	23%	13%	46%
	Predicted	9%	23%	12%	56%
	Difference	9%	0%	1%	-10%

In York 18% of actual journeys took place on off-road paths, with 16% in Cardiff and 12% in Bristol. 23% of journeys took place on on-road cycle lanes in York, which was higher than the other two cities with Bristol on 13% and Cardiff 11%. In Cardiff a higher percentage of journeys took place on traffic calmed/advisory routes (28%) than in Bristol (23%) and York (13%).

Overall 55% of journeys in Cardiff took place on routes with some provision for cyclists, 54% in York and 48% in Bristol, indicating that cyclists do modify their route in order to utilise provided cycling network facilities when considering the proportion of routes that have some facility incorporated (as illustrated on Figure 54, Figure 55 and Figure 56). For example when looking at the difference between the actual journey and model predicted journeys, an additional 15% of the predicted (i.e. most direct) journey took place on routes with no facilities.

The relatively poor agreement between actual and predicted routes therefore suggests that cyclists may have modified their route from the most direct (predicted route) to a more cycle friendly option in all cities. In both Cardiff and York 9% more of the journey took place on off-road facilities whereas in Bristol an increase of only 2% on off-road routes was observed. In Cardiff and Bristol 5% more of the actual journey took place on on-road facilities than the predicted journey whilst there was no difference between actual and predicted for on-road routes in York. Traffic calmed or advisory routes were used 8% more than the predicted in Bristol, 7% more in Cardiff and just 1% more in York.

9.3 Results from the individual cyclist behavioural questionnaire

9.3.1 Spatial variation of results

GIS was used to spatially analyse responses from the questionnaire within the three cities as described in Section 8.2. The location of the start point (home) of all respondents was mapped for each city, as shown in Figure 66, Figure 67 and Figure 68. These indicated that journey end points, as expected, were concentrated within the city centres. Journey start points were

much more scattered across each of the cities contributing to the difficulty in predicting routes that cyclists were likely to take and therefore where financial resources should be invested.

Table 19 illustrates the percentage of journey start points in each section of each of the cities. In Cardiff and Bristol cyclists were concentrated in particular areas of the city. In Bristol cyclists travelled from the north and east of the city centre (37% and 34% respectively). In Cardiff the majority travelled from the north (34%) and west (31%). These locations correspond with the main off-road cycle facilities in each city – namely the Bristol to Bath Pathway and the Taff Trail. In York the start points of journeys were more evenly distributed across the city.

Table 19 - Location of journey start points across each city

	Bristol	Cardiff	York
Section of city	Percentage of respondents		
Northern	37%	34%	20%
Eastern	34%	23%	22%
Southern	15%	12%	29%
Western	14%	31%	29%

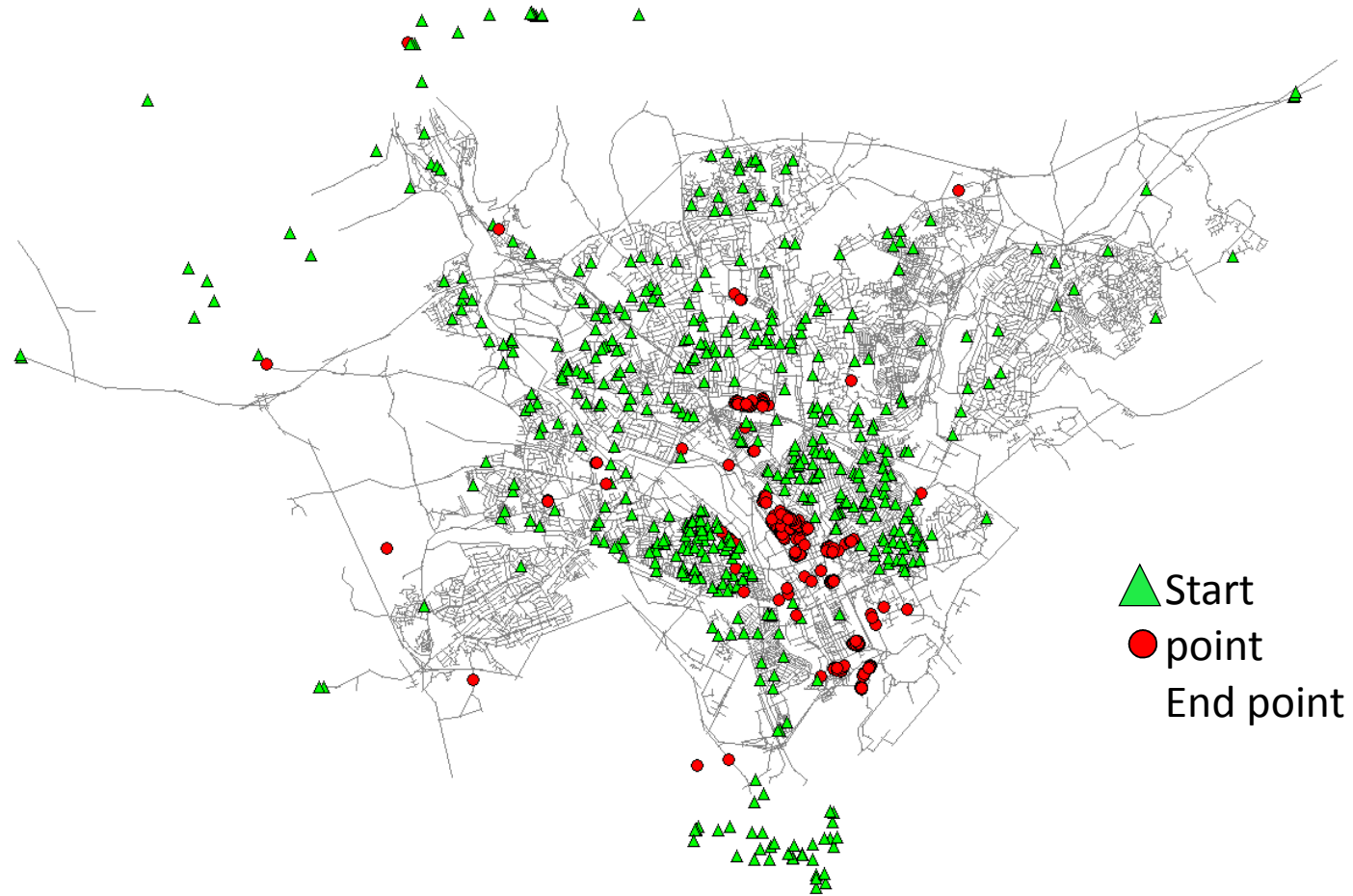


Figure 66 -GIS map of Cardiff illustrating the start and end points of all survey respondents

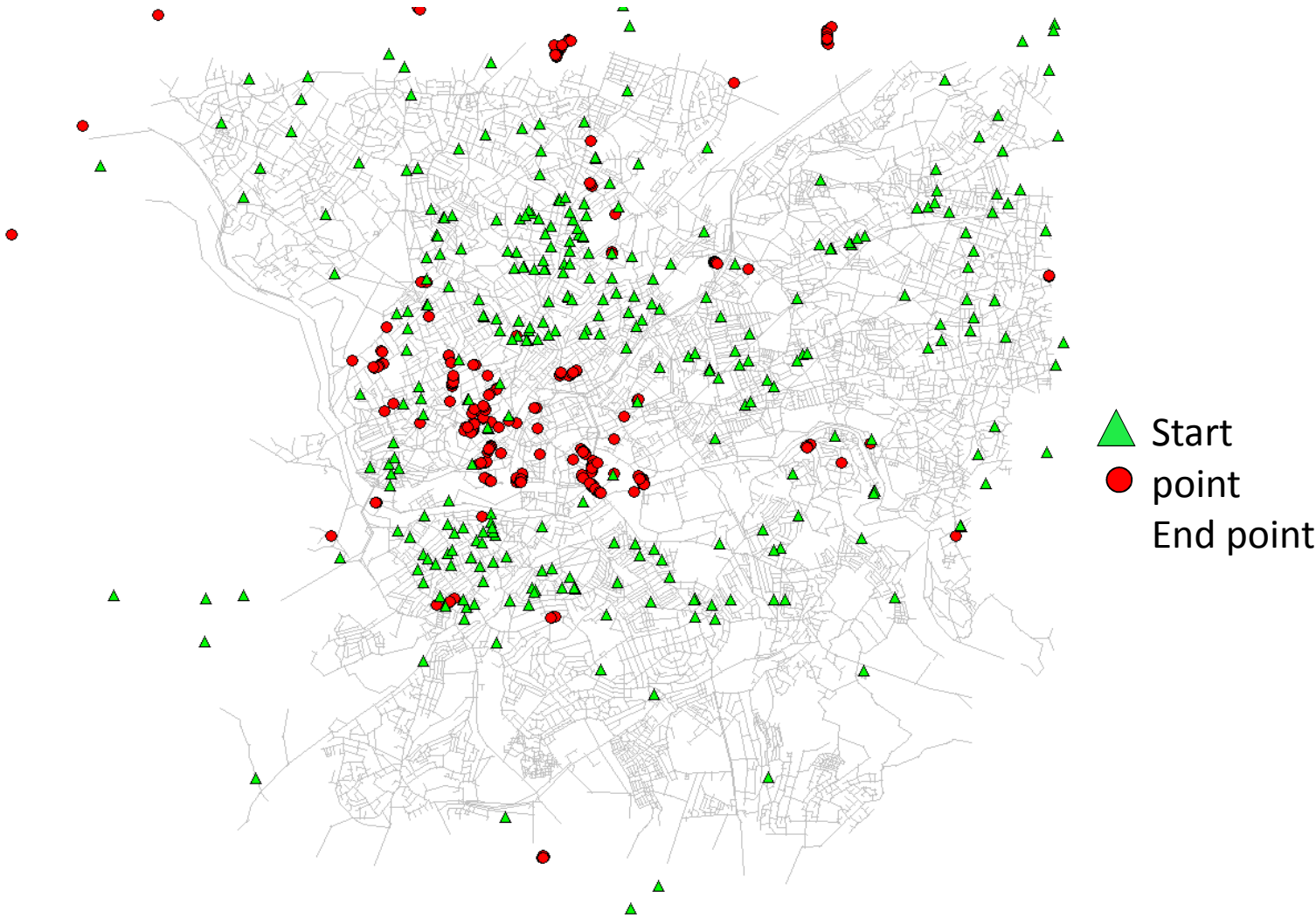


Figure 67 - GIS map of Bristol illustrating the start and end points of all survey respondents

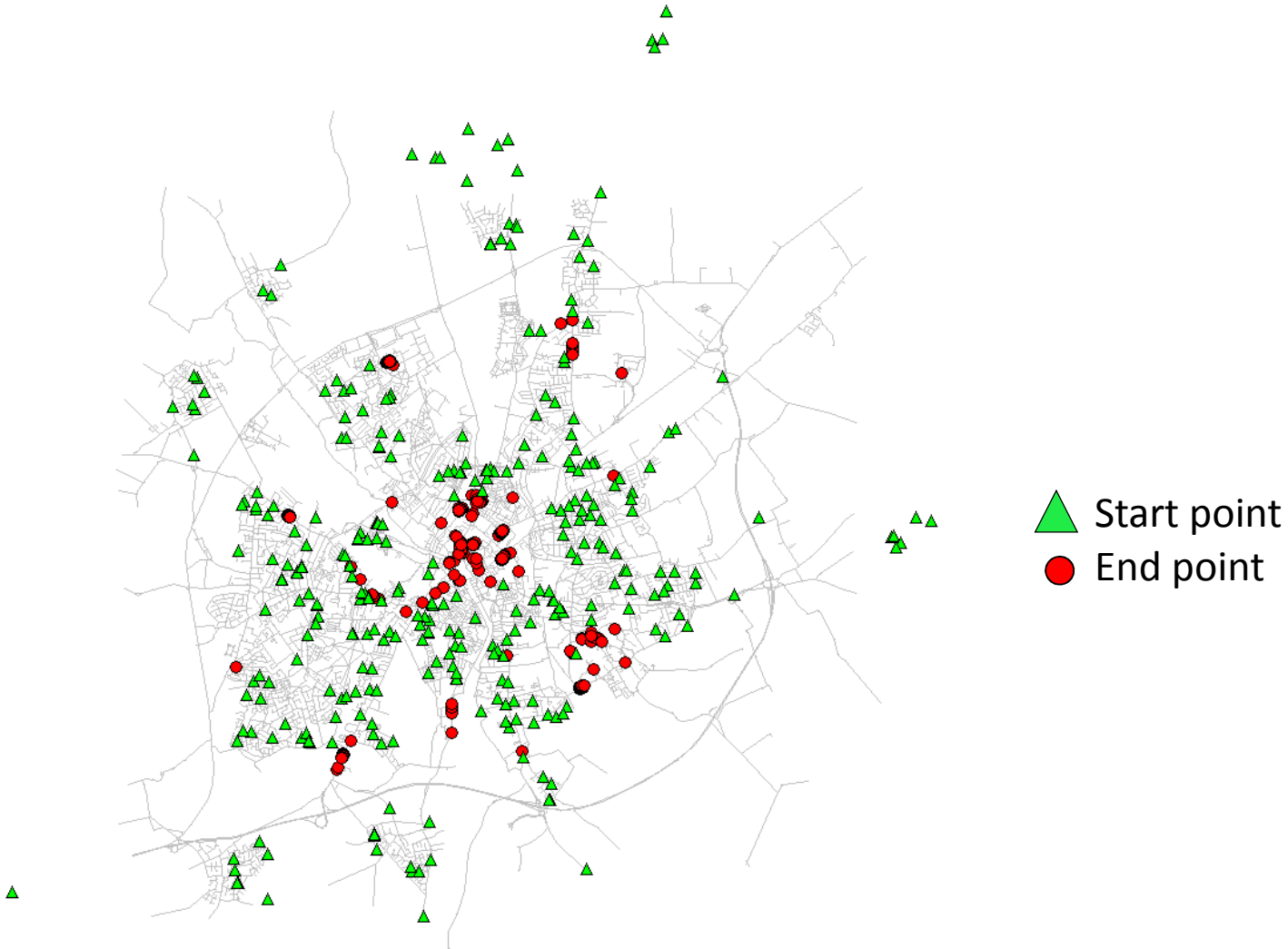


Figure 68 - GIS map of York illustrating the start and end points of all survey respondents

As part of the mapping exercise, within the questionnaire respondents were asked to identify any junctions that they perceived as being dangerous. 100 junctions were identified to be dangerous in both Cardiff and Bristol, with approximately 70 in York. In Cardiff, 30 locations were identified to be a perceived risk by more than four cyclists. The junctions at Gabalfa interchange and Wedal Rd/Roath Park junction were identified most commonly to have the greatest perceived risk. In Bristol and York 17 junctions were identified to be a perceived risk by four or more cyclists for both cities. In Bristol the area around Bedminster Bridge was perceived to a particular problem. In York, Bootham Bar was recorded to be a problem by 15 cyclists.

Although these results are likely to be affected by the sampling technique, the usefulness of being able to map dangerous junctions using GIS is illustrated and can be used to target problem junctions in each city. Results from the questionnaire indicate that 70% of respondents felt that they were at ‘much’ or ‘some’ risk at difficult junctions, which is likely to affect their route choice. If these junctions or connectivity of surrounding spaces can be improved for cyclists, more cyclists might be encouraged to cycle. If additional cyclist flow data was available the spatial analysis model developed and demonstrated in could be utilised to investigate these impacts.

9.3.2 Demographics of respondents

When considering the characteristics of the respondents, 66% of the responses were from males and 33% from females which corresponds with National Travel Survey statistics (DoT, 2012). The proportion of females who responded to the questionnaire in York was 6% higher than Bristol and Cardiff. Figure 69 illustrates the age groups of the respondents and indicates that almost one third were from each of the age groups 25-34 and 35-44. Respondents from

York were significantly older with 45% being over 45 years old compared to an average of less than 30% for this age group in the other two cities.

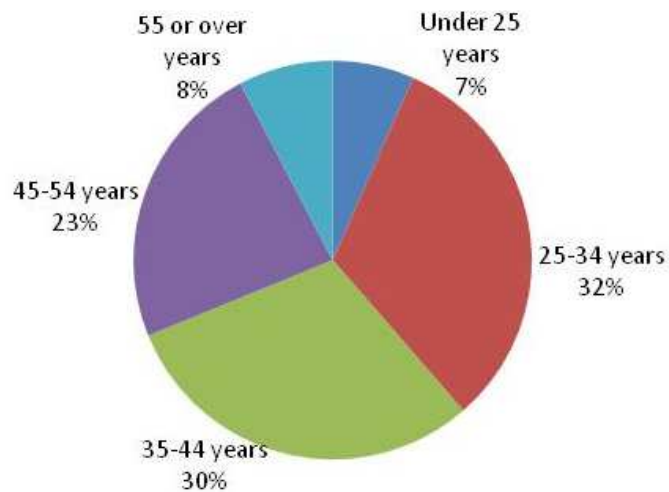


Figure 69 - Age groups of questionnaire respondents

Census figures indicated that the populations of Cardiff and Bristol were younger than that of York, with higher concentrations in the 15-25 and 25-34 age groups which could be influenced by Bristol and Cardiff being larger in size and having larger student populations as both have two universities within the city. When looking at general frequency of cycling across the three cities, it can be seen in Figure 70 that around half of the respondents cycled to work every day during both the summer and winter.

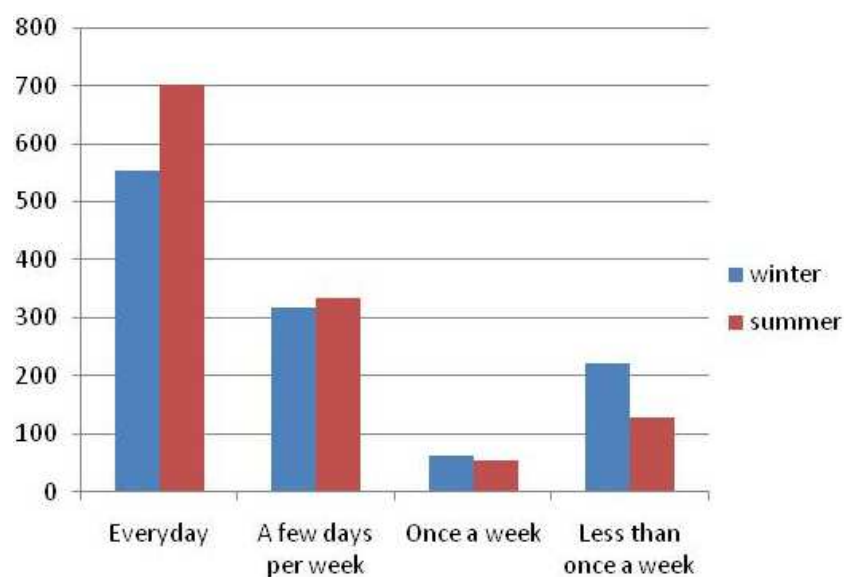


Figure 70 - Frequency of cycling for across 3 cities during summer and winter

Results show an overall 10% decrease of every day cyclists during winter, which can be explained by worsening weather conditions and dark mornings and evenings, whilst the number of people who cycled to work a few days a week remained largely consistent throughout the seasons. Cardiff had a higher overall percentage (almost 10%) of respondents who cycled less than once a week.

9.3.3 Journey characteristics

The distance travelled in all three cities was very similar with an average of 80% of respondents reporting that they travelled less than 5 miles to work as illustrated in Figure 71. This was higher than the 64% reported for England and Wales as a whole (ONS, 2014).

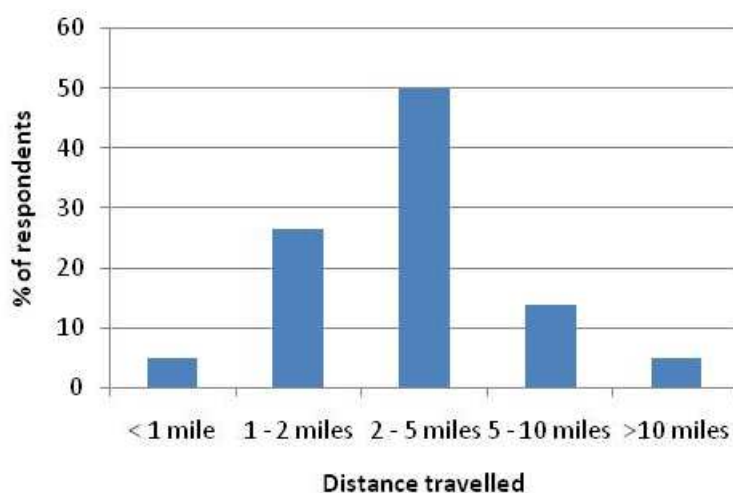


Figure 71 - Reported distance travelled to work by respondents

Results indicate that cyclists in Bristol were more likely to travel more than 10 miles. The existence of a long-distance, well-established motor traffic-free route (Bristol-Bath path) could be a factor as it serves outlying suburbs in the north and east of the city and makes commuting by bike easier from more distant locations.

When considering the time that it takes for respondents to travel to work (Figure 72), 78% of respondents reported that they cycled to work in less than 30 minutes. Journey times in York were generally less, even though distance travelled was similar.

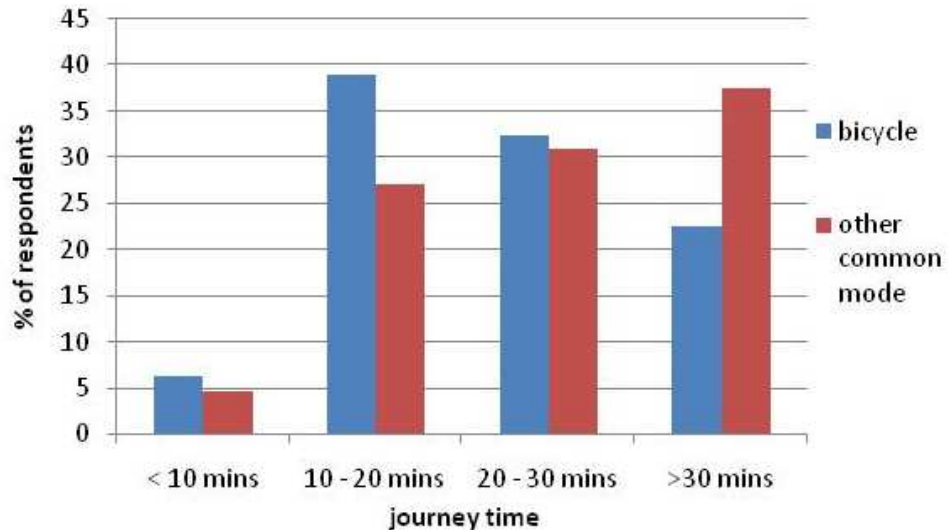


Figure 72 - Average journey time in minutes by bicycle and most other common transport

Figure 73 illustrates that for the commuters surveyed, the car was the most common alternative mode of transport to the bicycle. When comparing journey times by bicycle to those by car it was found that 15% more journeys by bicycle took less than 30 minutes than by car indicating a time benefit to commuting by bicycle. This favours cycling as an option and could be used to promote cycling to commuters (Figure 72).

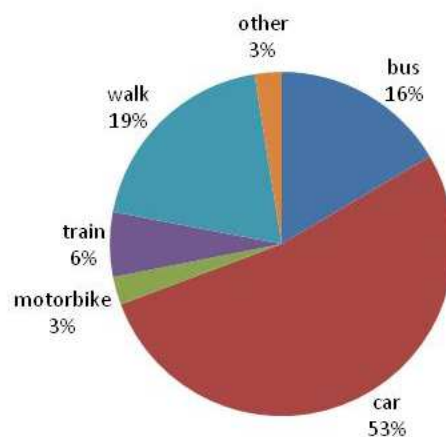


Figure 73 - Most common alternative mode of transport

On average 70% of the respondents had access to a car or van. Access to public transport as an alternative mode for the journey to work ranged from 70% in York to 80% in Cardiff. This is significant as the remaining 20-30% of the population have limited alternative travel options. Journey times for alternative transport methods were noticeably shorter in Cardiff and York than in Bristol.

When considering other alternative modes of transport, Cardiff was the only city with significant train use at 11% within the sample. This is supported by the response that Cardiff's public transport was rated as 'very good' or 'quite good' by 50% of respondents, compared to 41% in York and under 30% in Bristol. The population within Cardiff are well served with several branch-lines within and around the city boundary together with the Valley Lines which serve a wide area adjacent to the city. Smaller stations are located near the centre of the city in Cardiff including Cathays and Queen Street, these being very convenient for a number of large employment centres, increasing the attractiveness of travelling by train. Train options are also well integrated with bus services, as the main bus and rail stations in Cardiff are adjacent to each other. Contrast this with Bristol where the central bus station is on the other side of the city centre to the train station, making a journey combining bus and train difficult. There are no railway stations within 3 miles of the central rail station in York meaning that the option of rail travel is not available for short commutes into the City Centre. Although this station is well linked nationally, it does not provide a viable short distance commuter option.

These figures indicate that, rather than offering a real alternative to the car, public transport was perceived as an unfavourable option by at least half of respondents in each city. There are therefore opportunities, if cycling facilities were improved, to encourage car users to travel by bicycle, rather than public transport.

9.3.4 Route choice

When considering the journey made by bicycle, the most frequently used route type as indicated by respondents for all three cities were busy roads with no provision of specific cycling infrastructure, accounting for an average of 42% of each journey as indicated in Figure 74. This can be compared to 48% identified from the route indicated on the map within the questionnaires and 48% predicted by the model (Section 9.2). Quiet roads and dedicated cycle lanes on busy roads were the least used route as illustrated in Figure 74.

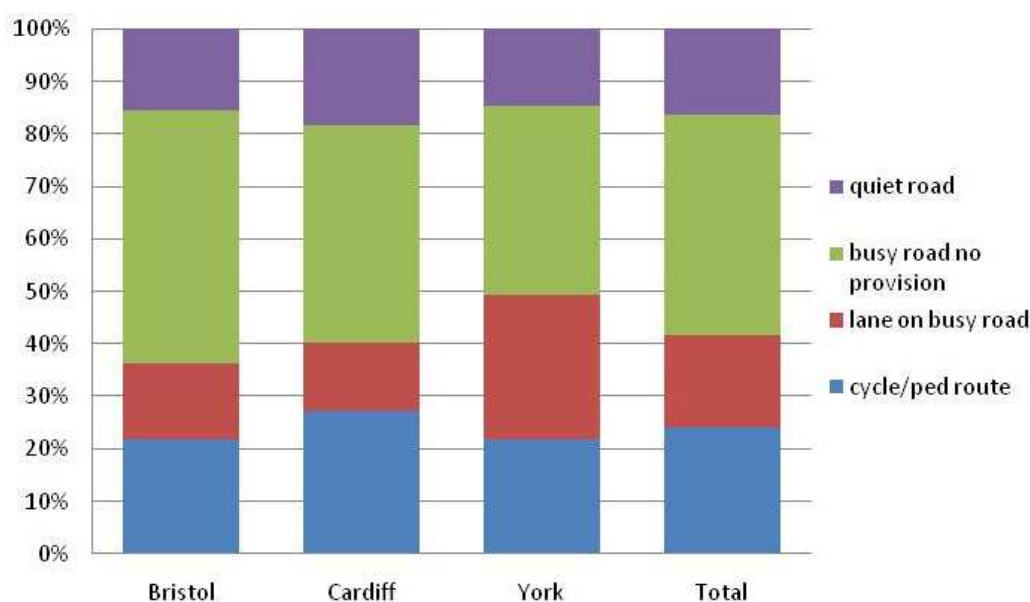


Figure 74 - Respondents approximate time spent on different route types when travelling by bicycle

Nearly 50% of cycle journeys in Bristol took place on busy roads with no cycling provision compared to 41% in Cardiff and 34% in York. 27% of journeys in York took place on cycle lanes on-road which was higher than the other cities due to the much higher provision of this type of facility in York. Cyclists in Cardiff spent more journey time on designated cycle routes than in any other city, which is surprising given the lack of off-road routes, particularly around the city centre. The Taff Trail may however account for many of these trips, which is a well

established off road facility linking a large population in the north of Cardiff to the centre of the city.

When considering the extent to which different factors influenced the route taken to work, Figure 75 illustrates that exposure to motor traffic was the most influential factor in route choice with 75% stating that this influenced their route choice to a great or moderate extent. Cycle lane provision was influenced to a great to moderate extent for almost 60% of respondents.

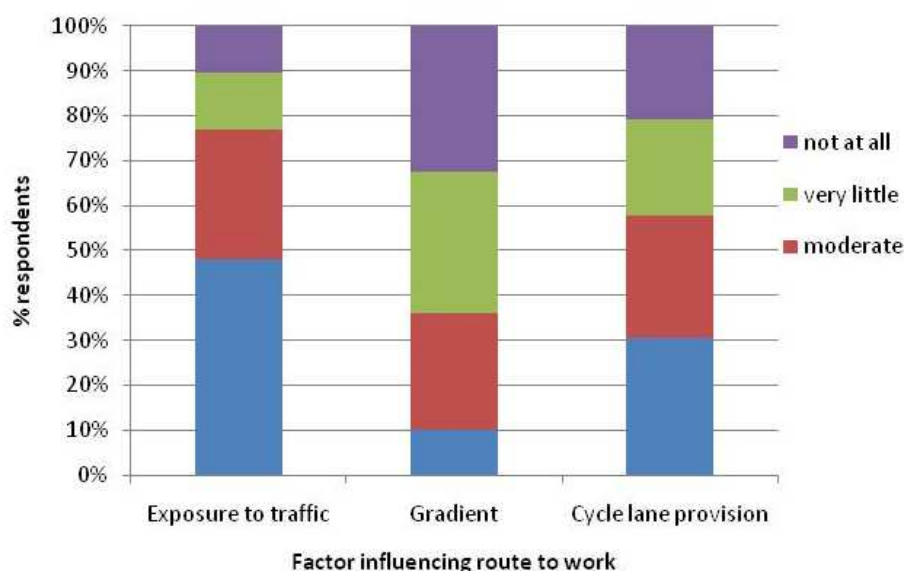


Figure 75 - Influence of various factors in route taken to place of work

Exposure to motor traffic was a far greater factor in influencing route choice in Cardiff with 84% citing motor traffic influencing their route choice by a moderate to great extent, as opposed to approximately 70% in York and Bristol. As might be expected, gradient was influential in Bristol (50% moderate to great extent) which has some very steep hills, but featured much less in Cardiff and York (between 20-30%) where the terrain is flatter. 70% of respondents believed they took the shortest route possible to their place of work when they cycle. This ranged from 78% in York to 62% in Cardiff. However, as indicated in Section 9.2,

only around 25% of journeys agreed with the most direct route calculated by the space syntax model, suggesting at least a degree of modification of the route in the majority of cases. This may be to avoid the faster flowing motor traffic on Cardiff's roads, which can act as a significant deterrent to cyclists. It is also likely that whilst respondents *believed* that they took the shortest route to work, it has been illustrated in Section 9.2 that this is not the case. Minor deviations from the shortest routes are likely to be incorporated into journeys to avoid perceived problem areas, or to utilise routes or facilities that are considered to enhance the journey.

9.3.5 Attractors / deterrents to cycling

The weather was identified as strongest overall deterrent to cycling in all three cities with over 50% stating it would deter them from cycling from a moderate to great extent, as indicated in Figure 76. Responses of between 40 – 50% (great to moderate extent) indicated that work or personal needs including multipurpose journeys, business during the day and the need to carry equipment deterred them from cycling to work.

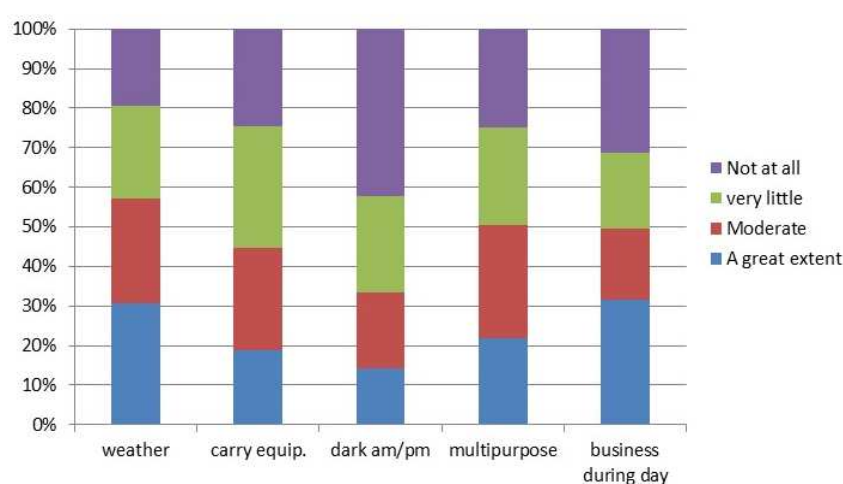


Figure 76 - Factors that deter cycling on any given day

With regard to danger experienced from other modes of transport, an average 90% of cyclists felt that they were at ‘moderate’ or ‘much’ risk from cars and vans. 70% of cyclists felt that they were at risk from public transport as illustrated in Figure 77.

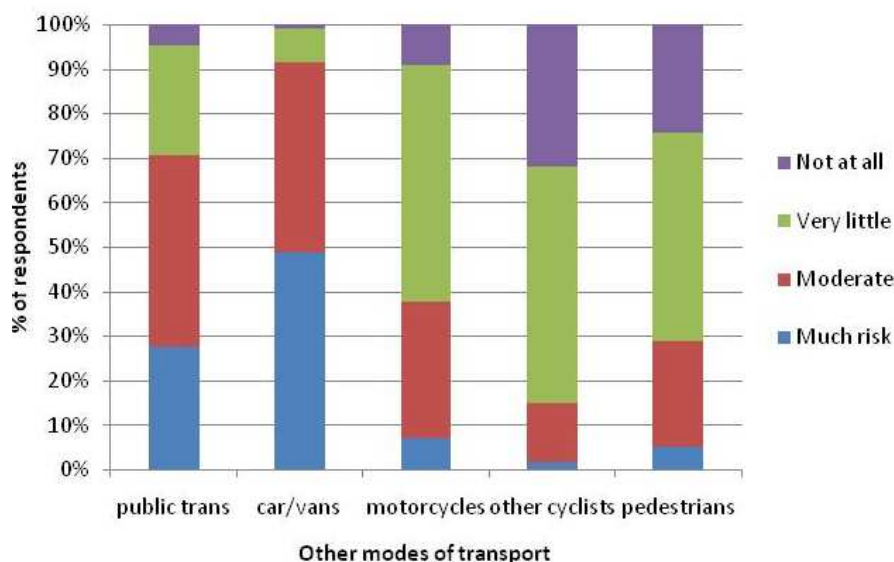


Figure 77 - Danger from other modes of transport

A higher percentage of respondents felt that cars and vans provided ‘much’ risk in Cardiff. This may be due to the relative lack of on-road provision for cyclists and the traffic speeds being slightly higher due to lower levels of congestion. Perceptions of danger from all sources including public transport, motorcycles, pedestrians and other cyclists were lower in York than the other two cities.

Figure 78 presents the stated importance of various factors involved in making the decision to cycle to work rather than to use another mode of transport. Over 90% of those surveyed agreed that health was a very/quite important factor in their decision to cycle to work. Environmental benefits were the next most frequently cited reason with a response rate of 80% (quite or very important), with independence and time-saving having similar responses. Many more people in York found that cycling shortened their route (or at least it was perceived to do so). Cardiff cyclists considered their employers to be less encouraging than in Bristol and York.

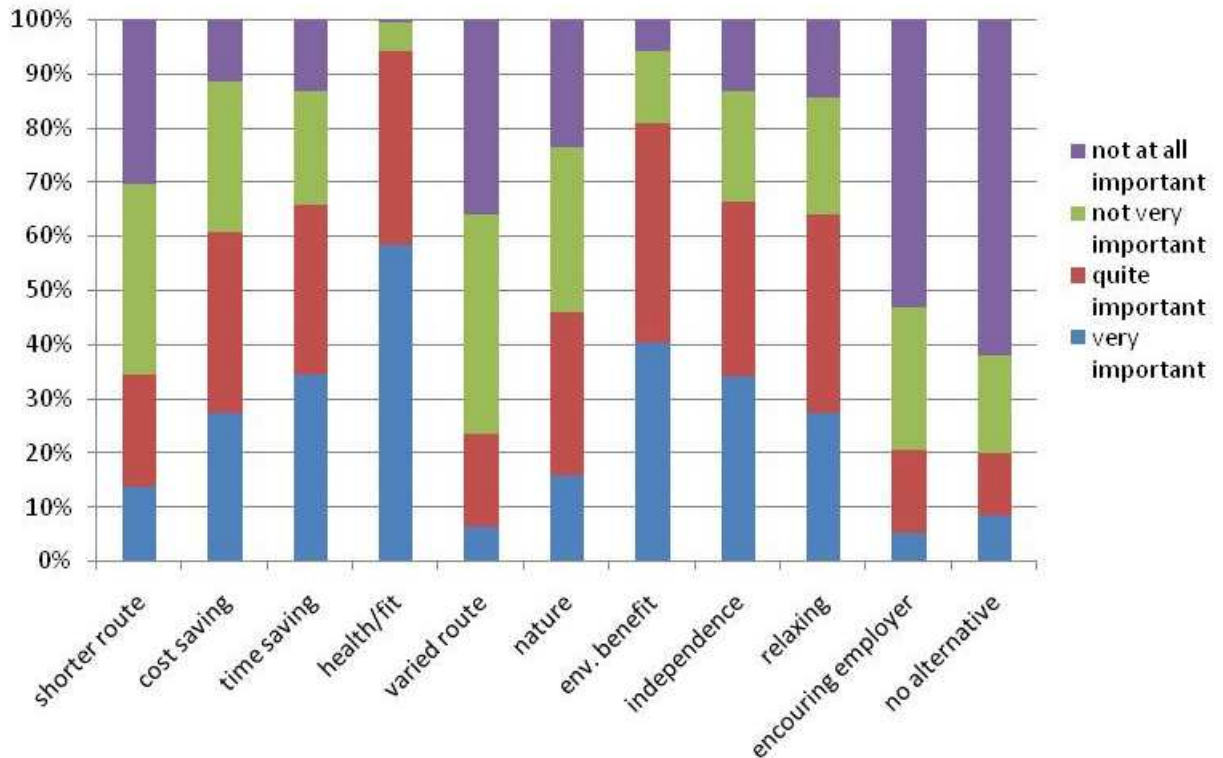


Figure 78 - Importance of various factors involved in making the decision to cycle to work rather than use another mode of transport aggregated for 3 cities

When considering factors that would encourage cyclists to cycle more often, results showed that safer routes (on/off road) would have the highest impact, as illustrated in Figure 79. More than 80% respondents agreed that this would encourage them to cycle more often. Better facilities at work and decreased road congestion obtained 65% response for moderate to great extent.

A lack of cycle lanes, personal safety, need to carry bags, formal dress, combining journeys, weather and danger from traffic were all reported as deterring cycling at either a moderate or great extent by around 50% of respondents (Figure 79). 87% of Cardiff cyclists (to a great or moderate extent) wanted safer routes to their workplace to encourage them to cycle more often, whilst Bristol and York respondents also placed safer routes as most important at 82% and 78% respectively.

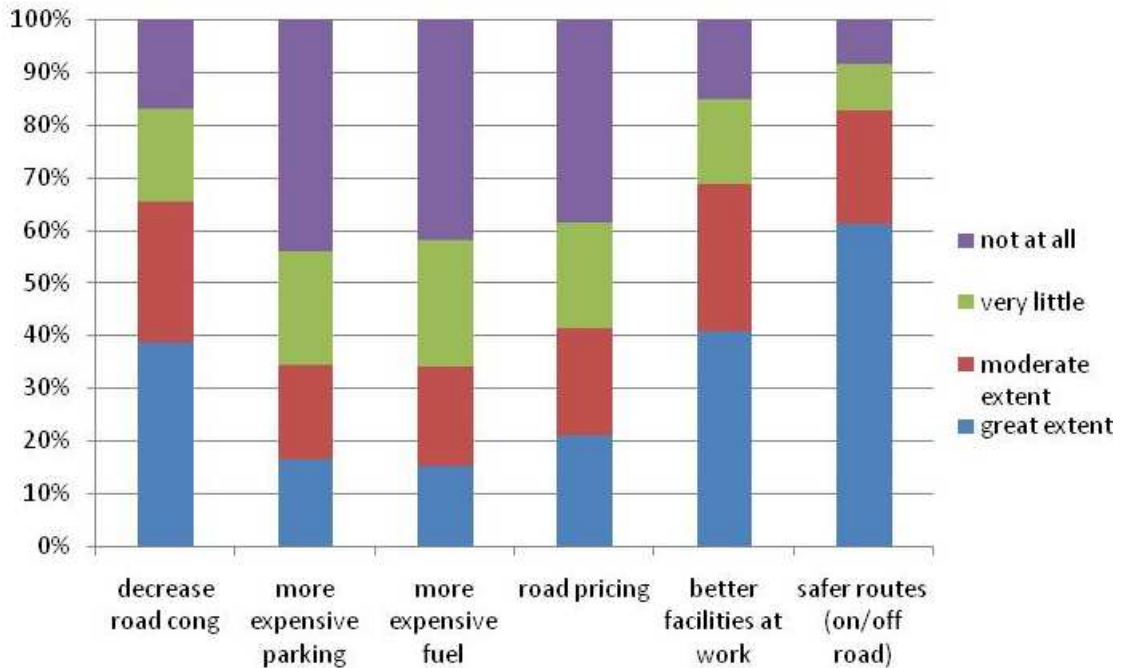


Figure 79 - Factors that would encourage cyclists to cycle more often

When considering risk faced when cycling, motor traffic was seen as the biggest *risk* in all three cities by an average of 90% of cyclists (from ‘some’ to ‘much’ risk) as illustrated in Figure 80. Difficult junctions are perceived as the second highest risk ranging 77% in Cardiff to 63% in York. The order of importance of risk was very similar for all three cities but once again figures for Cardiff are higher within the bands ‘some’ and ‘much’ risk.

It was reported that 80% of employers in Bristol provided covered, secure parking facilities for cycles, and 25% offered a bike loan. In Cardiff and York the corresponding figures were an average of 70% for parking and 10% for a loan. On average only 5% of respondents knew if a financial incentive to cycle to work was available.

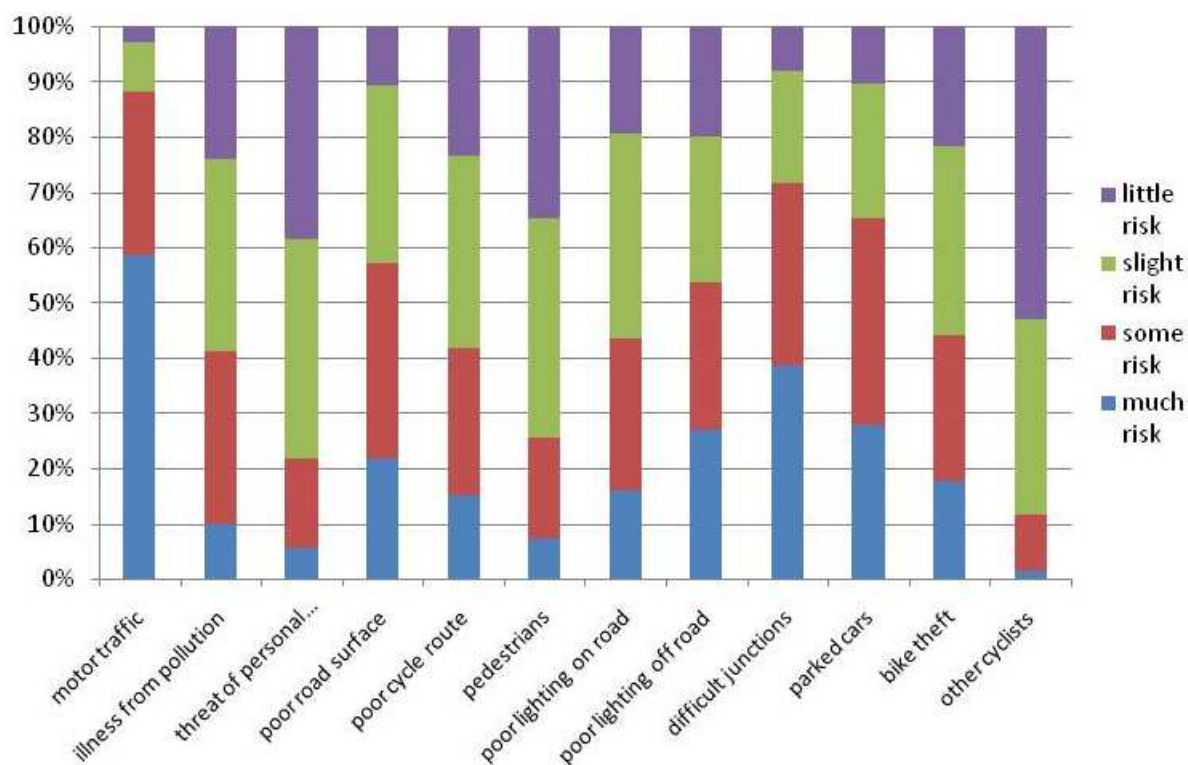


Figure 80 - Perceived risk reported by respondents when cycling to work

9.3.6 Frequency based analysis

Further analysis was undertaken using categorical regression analysis (CATREG) to identify the dominant characteristics in the decision to undertake a journey by cycle within different groups of cyclists using the methodology described in Section 8.2.3.

662 questionnaires were completed sufficiently (questions complete/correctly filled in) to be included within CATREG analysis. The overall CATREG result showed an adjusted R^2 value as 0.5 indicating that the independent variables predict the dependent variable (frequency of cycling) well, and so the regression model could be used as a good indicator of frequency of cycling. When considering the ANOVA result it can be seen that the process was non-random and therefore the results were considered as valid. The results of categorical regression analysis can be seen in Table 20.

Table 20 – Results table from categorical regression analysis (CATREG)

	Standardized Coefficients		df	F	Significance
Independent variables	Beta	Std. Error			
weather conditions - extent deters cycling	-0.277	0.047	2	35.053	0
dark mornings/evenings - extent deters cycling	-0.253	0.038	2	43.35	0
need to carry bag/equipment - extent deters cycling	-0.151	0.04	4	13.944	0
lack of dedicated cycle lanes - deter from cycling	-0.11	0.047	4	5.542	0
other mode journey time	-0.098	0.035	2	7.982	0
illness from pollution - risk	-0.097	0.033	3	8.778	0
cost saving - decision to cycle	0.086	0.032	4	7.191	0
sense of independence - decision to cycle	0.123	0.035	4	12.505	0
time cycling on quiet road	0.153	0.038	3	16.213	0
average journey time	0.238	0.051	3	21.727	0
no alternative - decision to cycle	0.103	0.031	1	11.376	0.001
varied route - decision to cycle	-0.087	0.035	2	6.119	0.002
night time lighting on roads- risk	0.083	0.034	2	5.929	0.003
need to carry bag/equip - deter from cycling	0.084	0.042	4	4.009	0.003
influence of cycle lane provision	-0.065	0.033	4	3.733	0.005
bike theft - risk	0.073	0.032	2	5.269	0.005
conflict with pedestrians - risk	0.085	0.037	2	5.396	0.005
journey length - deter from cycling	0.087	0.04	2	4.772	0.009
contact with nature - decision to cycle	0.081	0.04	2	4.155	0.016
environmental benefit - decision to cycle	-0.067	0.035	2	3.749	0.024
other cyclists - risk	-0.06	0.038	4	2.498	0.042
How dangerous are cars/vans when you cycle to work	0.06	0.035	2	2.98	0.052

time cycling on cycle/bus lane on busy road	-0.067	0.035	1	3.704	0.055
more expensive parking - encourage cycle more	-0.074	0.043	2	2.881	0.057
rating of public transport	-0.049	0.03	2	2.739	0.066
decrease in road congestion - encourage cycle more	-0.062	0.034	1	3.274	0.071
motor traffic - risk	-0.061	0.034	1	3.169	0.076
condition of cycle route - risk	0.056	0.035	2	2.541	0.08
multipurpose trip - extent deters cycling	-0.059	0.037	2	2.505	0.083
support from employer - deter from cycling	0.056	0.033	1	2.883	0.09
weather - deter from cycling	-0.068	0.045	2	2.252	0.106
time saving - decision to cycle	0.054	0.036	2	2.249	0.107
need to dress formally - deter from cycling	-0.051	0.036	2	2.071	0.127
difficult junctions - risk	-0.05	0.034	1	2.182	0.14
health/fitness - decision to cycle	0.041	0.029	2	1.949	0.143
How dangerous are pedestrians when you cycle to work	-0.052	0.037	2	1.908	0.149
poor physical fitness - deter from cycling	-0.049	0.037	2	1.811	0.165
hills - deter from cycling	0.063	0.047	2	1.8	0.166
time cycling on cycle/pedestrian route (no motor traffic)	-0.05	0.036	1	1.868	0.172
need to combine journeys - deter from cycling	-0.051	0.038	1	1.792	0.181
more expensive fuel - encourage cycle more	0.07	0.054	2	1.707	0.182
safer on/off road - encourage cycle more	0.05	0.038	1	1.744	0.187
inflexible working hours - deter from cycling	0.04	0.031	2	1.668	0.19
condition of road surface- risk	0.043	0.034	2	1.639	0.195
encouragement from employer - decision to cycle	-0.038	0.031	2	1.544	0.214
personal safety - deter from cycling	0.055	0.044	1	1.539	0.215

How dangerous is public transport when you cycle to work	-0.039	0.031	2	1.539	0.216
influence of exposure to traffic	0.043	0.035	1	1.532	0.216
night time lighting on off road cycle routes-risk	-0.039	0.033	2	1.375	0.254
influence of gradient	-0.041	0.036	2	1.324	0.267
shorter route - decision to cycle	-0.035	0.034	2	1.068	0.344
personal attack- risk	0.028	0.031	1	0.814	0.367
Sex	0.032	0.032	2	0.987	0.373
parked cars - risk	0.031	0.034	2	0.852	0.427
time cycling on busy road with no cycling provision	-0.034	0.038	2	0.833	0.435
How dangerous are other cyclists when you cycle to work	0.032	0.039	2	0.674	0.51
road pricing - encourage cycle more	0.026	0.045	1	0.322	0.571
better facilities at work - encourage cycle more	-0.029	0.035	4	0.697	0.594
distance from door to door	0.03	0.045	2	0.432	0.649
How dangerous are motor cycles when you cycle to work	0.02	0.032	2	0.412	0.663
Do you take the shortest route	-0.017	0.031	2	0.3	0.741
danger from traffic - deter from cycling	-0.022	0.042	2	0.275	0.76
age	0.015	0.031	2	0.229	0.796
business travel - extent deters cycling	-0.014	0.035	2	0.161	0.851
relaxing experience - decision to cycle	-0.015	0.037	4	0.157	0.96

On reviewing the CATREG results, 21 variables out of the 65 included had a significance of $p > .05$. That is, to a certainty of 95%, they were predictors of the result, these are indicated in 20. The standardized coefficient Beta column indicate the results for each frequency group. Scores with a greater negative result indicate that the independent variable has a stronger influence on occasional cyclists, as the standardized coefficient Beta score increases, the independent variable is more relevant to the frequent and everyday cyclists.

The factors identified to have the strongest influence on *occasional* cyclists to a much greater degree than other cyclists included, in order of predictive coefficient:

- weather - occasional cyclists deterred by bad weather;
- dark mornings/evenings - occasional cyclists deterred by darker conditions;
- *average journey time* - occasional cyclists deterred by perceived longer journey times;
- *time spent cycling on a quiet road* - occasional cyclists deterred by lack of quiet roads;
- need to carry a bag/equipment - occasional cyclists deterred by the need to carry items;
- *lack of dedicated cycle lanes* - occasional cyclists deterred by a lack of dedicated cycle lanes.

Average journey time, time spent cycling on quiet roads and lack of dedicated cycle lanes are characteristics that could potentially be improved by infrastructure changes and improvements in connectivity. Results indicate that perceived journey length had little significance on the decision to cycle by the occasional cyclists group. Therefore occasional cyclists could be encouraged to cycle more often if:

- routes were improved to make them quicker, for instance by removing factors that cause cyclists to get off their bicycles, such as difficult road junctions;
- provision of signs and maps to improve knowledge of areas which would help direct occasional cyclists onto roads that were quieter than the main routes that they were more familiar with when using a car or public transport;
- cyclists were provided with a level of protection from motor traffic, through on-road cycle routes, they may be encouraged to cycle more often.

Factors identified to have the strongest influence over route choice for *frequent cyclists* that had a significance of $p > .05$, were:

- night time lighting on roads - more influenced by night lighting;
- conflict with pedestrians - more influenced by concerns over conflict with pedestrians;

- *the length of the journey* - more influenced by journey length;
- contact with nature - more influenced by potential for contact with nature.

An improvement in lighting on common routes would improve conditions for all cyclists and would have an overall impact on safety for the public in general. More clearly marked cycle paths and cycle routes may address the issue of conflict between cyclists and pedestrians together with on-road facilities where pedestrians are not an issue. The length of journey was also identified as having an influence over frequent cyclists. This could be explained by the fact that some frequent cyclists, as reported in the questionnaire, have limited alternative modes of transport resulting in cycling being a necessity. Occasional cyclists may only cycle when it appeals to them. Finally more frequent cyclists were more influenced by contact with nature, therefore more cycle paths through green areas and parkland could be preferential to this group.

From the CATREG analysis, the main factors that differentiated *everyday* cyclists from other frequency groups were sense of independence that cycling gives them; cost saving; no other alternative. These are generally personal factors that cannot be influenced by direct planning by local authorities.

9.4 Summary

The comparison between predicted and actual route choice has indicated that, at a fine level, the model was not particularly successful at predicting individual route choices which is perhaps not surprising as the modification of the route chosen from the most direct route is based on human choice. For example, cyclists may be more deterred by the time it takes to make a journey than the actual geographical length of a journey, or that they may increase the

distance travelled to experience a more pleasant journey on routes with cycle facilities. As such, whilst the survey respondents used for this research believed that they had been taking the most direct route for their journey, this may not necessarily be the case with only 25% accurately predicted by the model. Deviations from the most direct route to either avoid problem areas (e.g. busy junctions) or to utilise favoured infrastructure (e.g. an off road route) are likely to be incorporated into cycle journeys either without the conscious lengthening of the journey or without consideration of the most direct route as a viable option. Future research to further incorporate weighting factors based on the cycling hierarchy could improve this by weighting more favourable routes. However, a greater understanding of cyclist behaviour is required in order to inform any future modification of the modelling approach.

Survey results showed that cyclist behaviour, including the route taken and whether to cycle or use alternative transport, was influenced by a wide range of factors, many of which were based on the perceptions and personal choices of the individual at any given point in time. This makes the behaviour of cyclists difficult to predict, particularly when, as is the case for this thesis, survey results are limited to a one off occasion and long term reliable data on cycle movement patterns is not collected by local authorities. However, it is clear that certain factors affect the choice of whether or not to cycle across the range of respondents. The safety aspect and risk associated with motor traffic was found to be the overriding issue with regards to route choice, and results also indicate that respondents are prepared to travel further to travel on routes that have less motor traffic and are therefore perceived to be safer.

Chapter 10: Discussion

10.1 Performance of the basic spatial analysis model for motor traffic flow

A process of validation for a motor traffic flow spatial analysis model has been presented. This validation process was undertaken through a series of stages to identify the minimum level of data that needed to be collected in order to implement the model effectively. Initial tests using global integration values and average hourly traffic flow figures for a limited number of main routes produced a weak correlation with an R^2 value of 0.07 (Figure 33, Section 5.2). This result was not unexpected as data points for measured motor traffic flow were limited both in number and in the types of roads included within the analysis, meaning that the dataset being used for correlation was itself limited in its ability to reflect the range of average hourly traffic flows across an urban area. In addition, the spatial analysis model in its basic form did not accommodate factors which affected the flow of motor traffic along any particular road, such as attractors or deterrents to motor traffic, and did not account for motor traffic entering/leaving areas when not considered as part of a geographically larger model. As such, it can be concluded that the range of the initial dataset was below that required to validate the motor traffic flow model and that a greater level of motor traffic flow data would be required.

By increasing the range and number of motor traffic flow data for a smaller case study area the correlation between average hourly motor traffic flow and global integration values was improved with R^2 value of 0.68 calculated when the case study area was considered as part of the larger city wide model, i.e. was not isolated (Figure 36, Section 5.3.1). However, regardless of the larger dataset used, correlation values did not improve when the case study area was treated as an isolated area, i.e. the larger city wide axial map was not associated with the smaller area, with an R^2 value of 0.05 achieved (Figure 40, Section 5.3.1). This is because roads at the boundary of the axial map, or at the boundary of an isolated area within an axial map, were modelled as being less well connected when in fact this was not the case as the

model only has data from within the area on which to base the integration calculations. The nature of the transport infrastructure and motor traffic flow data from outside of the mapped area was unknown and therefore was not considered within the model calculations, i.e. flow across the boundary was not represented within the model. This was the case when city/region wide areas were modelled, with roads at the edge of the axial map being considered less well integrated than those at the centre, or when smaller sub-areas were considered in isolation. By modelling a sub-area whilst taking into account the connectivity of roads across the whole city region, the 'edge effect' was mitigated, therefore improving correlation with measured motor traffic flow. It can therefore be concluded that increasing the validation data set to represent a wider range of motor traffic flows and road types significantly improved model correlation when non-isolated areas were considered. However, for isolated areas the 'edge effect' dominated model calculations to the extent that this improvement in model correlation was not evident, meaning that some method of compensating for edge effect would be required to improve the correlation.

When data was analysed for a range of motor traffic flows for the case study area (Figure 37, Section 5.3.1) it was found that global integration values from the spatial analysis model correlated well with motor traffic on roads with traffic flows of greater than 100 vehicles per hour (R^2 of 0.65) but not so well on roads with traffic flows of less than 100 cars per hour (R^2 of 0.016) (Figure 38, Section 5.3.1). There were a number of factors that contributed to this result. Firstly, roads with higher traffic flows included routes such as urban clearways that are used relatively consistently by the aggregate population. Journeys along these roads are likely to be made by people passing through the area to reach key destinations such as the city centre. Small day to day variations in flow on these roads have a relatively minor impact when compared to the overall motor traffic flow and this level of consistency on major routes makes the prediction of motor traffic flow more possible. It is also worth noting that these high traffic

flows are generally as a result of the major roads being well connected. Conversely, roads with low motor traffic flows tended to be not as well connected to the wider network, and journeys were more likely to originate or end nearby as individuals travel to or from more connected routes. Low motor traffic flows mean that day to day variations, which are driven by individual choice rather than an aggregate population, make them more difficult to predict accurately.

In order determine whether further increasing the data set would further improve model performance the number of sampling points and range of road types across the whole city for which flow data was available was further increased, and once again compared to calculated global integration values (Figure 43, Section 5.3.2). The correlation between average hourly traffic flow figures and global integration was slightly improved but not to the extent that the model could be considered functional for purpose. This further increase in the number of sampling points would incur additional time and cost to collect, collate and model for little additional benefit and would mean that the model would not meet the aim of being easily applied. It can therefore be concluded that this level of motor traffic flow data exceeds that required to validate the model.

The effect of replacing global integration with radius integration (Section 5.3.3) was investigated as a potential means of improving model performance by placing emphasis on the local connections associated with axial lines. Radius integration was developed to investigate local integration (Dalton, 2007; Turner, 2007) which is particularly relevant to pedestrians where movement from a place of origin is limited by physical ability, with the effects of accessibility and connectivity being more limited. Radius integration allowed local movements to be reflected in the integration values calculated. Tests concluded that the correlation between average hourly traffic flow and radius integration calculations (at levels 3 and 7) were weaker than global integration calculations (

Table 10, Section 5.3.3). This is likely to be because a wider urban network is accessible by car due to the ability to travel greater distances, and therefore radius integration is less significant as further distances/axial lines are accessible by car. This is supported by the work of Manum and Nordstrom (2013) and Law et al. (2013) who found that higher radius measures correlate better than lower radius measures with flow of cyclists, which is likely to be because cyclists are generally able to travel further distances than pedestrians. As a result of the weak correlation between motor traffic flow and radius integration values, the methodology for radius integration was discounted as an appropriate integration technique at an urban scale for motor traffic flow.

Given the limitations of the basic spatial analysis model in representing motor traffic flow as described above it was evident that the spatial analysis model needed to be improved to represent motor traffic flows to a level of accuracy that is satisfactory. Modification of the model using weighting factors was therefore investigated.

10.1.1 Evaluation of the weighting methodologies applied to the spatial analysis model for motor traffic flow

A series of different weighting factors were investigated to determine whether individually or in combination they could address some of the model limitations and improve the correlation between predicted relative motor traffic flows and measured motor traffic flows.

Boundary weighting methods, which allowed for motor traffic flow across the perimeter boundary of the area being modelled, were tested on a case study area to investigate the impact both of weighting factors and weighting locations. Tests on the case study area indicated that boundary weightings significantly improved the correlation between motor traffic flow and

integration values compared to when the area was treated in isolation with R^2 increasing from 0.05 to 0.875 (Table 11, Section 5.4.1.1). This was an improvement on the initial global integration values calculated when the case study area was considered a sub-area of the axial map of the whole city (R^2 0.68) (Figure 36, Section 5.3.1). This indicates that the boundary weighting facility was successful at accommodating the movement of motor traffic across a model boundary and therefore improving the ability of the model to predict motor traffic flow to a relatively high level of accuracy for a small area. It can therefore be concluded that boundary weighting when considering smaller, isolated areas, is a valid means of representing the movement of motor traffic across the area boundary.

The most successful boundary weighting method for the case study tests used a relative weighting factor based on 'hourly traffic count' at each 'non-built up' and 'built up' route into the area. This method of weighting incoming motor traffic was considered replicable as there would be a limited number of locations with these classifications at the boundary of an area and also these routes would be most likely to have recorded motor traffic flow data available. The method therefore meets the overall aim of the model in terms of its ease of implementation. Two tiers of boundary weighting were included within the model – 'connections' and 'levels'. Only three tests where the second tier of boundary weighting, 'level', was used produced a valid result. When considering the tests that were valid when using both connections and levels, the data indicated that there was a limit to the number of connections and levels that could be applied before a null result was obtained when undertaking analysis. When boundary weighting was applied to the whole of Cardiff there was a slight improvement in correlations when compared to basic global integration values but overall the improvement was not significant (R^2 increased from 0.3 to 0.37) (

Table 12, Section 5.4.1.2). The most successful boundary weighting tests applied used core and country roads which is a local method of classification and is therefore not easily transferable to other areas and does not achieve the stated research objectives. It is believed that the reason that boundary weighting method was not as effective at the city scale was that, at this larger scale, the edge effect had less overall influence on the integration values calculated due to the large number of axial lines present within the full map. Whilst the edge effect is significant close to the boundary, compensating for this had relatively little impact on the connectivity of the network towards the centre of the axial map. Conversely, for small isolated areas containing a limited number of axial lines, the edge effect would influence the connectivity of a greater proportion of the roads being modelled.

For the majority of tests undertaken on both the smaller case study area and the city wide area, valid results were generated when running the integration calculation within MapInfo. Incidents of ‘null’ returns occurred when the weighting method required the addition of relatively high numbers of both connections and levels at the boundary weighting locations. This was found to not be significant at the smaller case study scale as the level of motor traffic at the boundary was limited due to the physical size of the study area and therefore correlations between real motor traffic flow and integration values are relatively strong, indicating that the boundary weighting method was successful. However, due to the large number of axial lines within the city scale map, there is a need for significantly more ‘connections’ and ‘levels’ to be added at the boundary of the space being modelled. The capacity of model to associate appropriate levels of motor traffic flow at the boundary of such a large axial map does not seem to be possible at present. It can therefore be concluded that currently the additional effort of undertaking boundary the weighting methodology cannot be justified by the small improvement in correlation values obtained when considering the city wide area. However, if modifications to the algorithms within the spatial analysis model could be implemented to

include a higher number of connections and levels, there is potential for the boundary weighting to be successful at the city/region scale, as it has been for at a case study scale.

A number of tests to investigate the effectiveness of road weighting, allowing for road characteristics that might encourage/discourage motor traffic flow to be incorporated, were undertaken at a city scale both with and without boundary weightings. The road weighting method was chosen to be replicable in other areas and to be relatively consistent over short periods of time and was therefore based on national classification of roads. Correlations between integration values and average hourly traffic flows were significantly improved from R^2 of 0.06 to 0.72 when road weightings were applied (Table 14, Section 5.4.2). The reason that the road weighting method was effective at the city scale was because the classification system that is used as a basis for the weighting methodology identified the roads that have higher relative traffic flows and the weighting factors used are ordered to reflect their relative importance based on the national classification given. These roads are likely to be well connected and are therefore used relatively consistently making the prediction of motor traffic flow more possible. As previously described, journeys along these roads are likely to be made by people passing through the area to reach key destinations and, at an aggregated level, are relatively consistent and therefore more predictable by nature. Overall, it can be concluded that road weighting, based on national road classification, is an effective weighting methodology and meets with the overall model aim of being relatively straightforward to implement.

The road weighting figures utilised within the study are based on the relative importance of each road type as expressed by the road classification. An alternative approach might be to base the weighting factors on measured average motor traffic flow. For example, Table 8 illustrates the road weighting factors that could be applied for Cardiff based on a normalisation

factor of the average flow on a minor route. Where a representative range of average motor traffic flow data is available this may prove to be a more accurate weighting approach, however, as the aim of the research was to develop that is transferable to areas that might lack this data, in the research presented it has not been applied.

Table 21 – Alternative normalised weighting factors that could be used for road weightings based on classification of roads

	Motorway	Non built up principal route >30mph	Built up principal route ≤ 30mph	Minor routes
Average motor traffic flow for Cardiff	4,922	2,008	1,523	268
Normalisation factor	268	268	268	268
Normalised weighting	18.4	7.5	5.7	1

The improvement when road weighted integration values were combined with boundary weighting was only slightly higher than when road weighting only was applied (Table 14, Section 5.4.2). This suggests that road weighting was far more significant in terms of improving the ability of the spatial analysis model to predict relative motor traffic flows in line with measured motor traffic flows, and that therefore the additional effort required to implement boundary weightings may not be justified at a city scale. To improve the effectiveness of boundary weighting at this scale may require that the algorithms within spatial

analysis model are altered to increase the number of connections and levels that can be accommodated at the model boundary.

The most successful weighting methodologies were tested on three other cities/regions to investigate transferability of the methods. The tests implemented were selected based on the correlation results achieved when applied to the whole of Cardiff, the most replicable methods and need for data to undertake the test. Global integration was run for each of the three cities/regions. Three tests were then carried out to correlate motor traffic flow figures with integration values. Available motor traffic flow data for the additional cities/region was considerably more limited than was the case for Cardiff, with data mainly limited to motorways, non-built up and built up routes. However, this would also be the real world situation in other city/regions, and as one of the core aims of the spatial analysis model was that it should function with the limited data sets routinely gathered by the majority of local authorities and not require large additional investment for data capture, its application in this context was considered as appropriate to the scope of research. Boundary weightings and road weightings were seen to improve the correlation between average hourly motor traffic flow and integration values for Leicester and NPTCB (Table 15, Section 5.5) with maximum R^2 values of 0.39 and 0.86 achieved in each region respectively. It can therefore be concluded that the general space analysis modelling methodology and the weighting methods developed are transferable to other urban areas and can be implemented using readily available levels of motor traffic data.

Cahill and Garrick (2008) suggested that comparisons should be made against other transportation forecasting models to provide validation. This was undertaken within this thesis for the motor traffic flow model, with comparisons made between space syntax and SATURN. Results (Table 15, Section 5.5) illustrate positive correlations between the outputs of both models, as found with average hourly motor traffic flow data, indicating that additional data

from SATURN could be used to validate the model further if required. Qualitative, visual comparative analysis of results from Space Syntax and SATURN made by Barros, Silva and Holanda (2007) highlighted that all streets in space syntax had data ascribed to them compared to SATURN, which demonstrates an advantage of space syntax. Their comparisons found a good association between actual motor traffic flow figures from a limited amount of speed control devices (31 locations – arterial and collector streets only, not minor routes) and space syntax results and they are supportive of space syntax as not a large amount of data is required compared to other transport models, and the relatively high R^2 values achieved encourages the application of configurational models for motor traffic studies even if at the initial planning stage (Barros, Silva and Holanda, 2007). Unfortunately, the work in the study by Barros, Silva and Holanda (2007) was carried out at a UNESCO world heritage site in Brazil on unusual urban planning development, and is not considered particularly replicable to other urban areas. The results from this thesis demonstrate that data obtained from the spatial integration map are similar to results generated by the SATURN model, but require much less origin/destination based data, and therefore less expense, to make the calculations and can therefore be considered a suitable alternative at the initial planning stage.

Results of the correlation between measured and predicted motor traffic flow generated using both linear regression and spearman's rank correlation coefficient have been presented. In some cases within the data sets, the distribution of measured motor traffic flow available for a study area was not normally distributed, which indicates heteroscedasticity of the data. For example, Figure 36 indicates that there are sub-populations with possible different variable properties. This has been identified within the thesis through the analysis of the data set in Figure 37 and Figure 38 being split to indicate that the model may be able to represent motor traffic flow on roads of higher levels of flow but not on roads with a lower flow.

It is therefore acknowledged that the results provided using linear regression may not be accurate. In order to remedy this, it might have been possible to apply a numeric transformation (e.g. log or square transformation) to adjust the data set towards a normal distribution. If this was undertaken it is possible that a stronger correlation and therefore more accurate modelling would have been achieved.

The distribution of measured motor traffic flow data is likely to vary between study areas, for example, between cities / regions, or between different sub-areas within the same city / region depending on the characteristics of the transport network. As such, the requirement for performing this numerical data adjustment would have to be determined by the end user prior to undertaking the modelling work. Additionally, the end user would have to determine which numerical transformation method would be most appropriate to provide data that is as near to normal distribution as possible. These additional calculations conflict with the objective of providing a modelling method that has low data requirements and is fully transferable between cities / regions. The use of spearman's rank correlation coefficient, whilst providing a slightly less statistically powerful assessment of correlation between measured and predicted traffic flow, can at least be applied to data sets that are not normally distributed and do not require any additional data transformation in order to produce valid results. Of the results presented in this thesis, it is therefore concluded that those produced using spearman's rank correlation coefficient are the most valid across the data set.

10.2 Application of spatial analysis model to city scale cycle networks

An urban scale cycle route map containing all potential routes available to cyclists was created that could be used to represent relative cycle flows. These maps were created by making relatively minor modifications to motor traffic axial maps, which have been validated within

this thesis. The axial map for cycle routes contained around 30% more axial lines than the road axial map for the same city indicating that the additional resource required to make the amendment to the map is minimal. Application of the space analysis model to represent relative cycle flows (Appendix 2) demonstrated that the technique was capable of representing cyclist movement patterns along on and off road cycle paths as well as along roads with no cyclist provisions. The model was flexible enough to allow adaptation to include movement of cyclists through open spaces (e.g. parks) and to include small connections that are only accessible to pedestrians/cyclists and not to motor traffic such as minor paths between buildings.

The spatial analysis model has been used to investigate the impact of incorporating additional axial lines into the cycle network to simulate the improved connectivity within the cycle network that could be achieved through targeted, but limited, network improvements (Figure 57 and Figure 58, Section 7.2). Visual assessment of the output showed an overall shift in the 'centre' or most connected part of the axial map was seen towards the location of the additional axial lines. The impact of this was not as visually obvious as would be expected, with well connected routes across the map remaining relatively well integrated, regardless of their location in relation to the newly added axial lines. It is believed that the combination of the additional axial lines, and therefore connectivity would be enhanced with the route weighting factor incorporated.

Within this thesis replicable weighting factors were applied to a case study cycling axial map to demonstrate that the weighting methodology that was successful with regard to road motor traffic flows could also be applied to represent preferential cycle flows along key routes. Route weightings have been applied to a case study area for cycle flows, using a route hierarchical methodology similar to that used for road weighting within the validated motor traffic flow

tests. The weighting facility could potentially be used to represent preferential routes for cyclists providing a resource that could be used to investigate the impact of modifying cycle network infrastructure. For example, the addition of new on or off-road cycle routes could be included within the model as a new line of connectivity (Figure 62 and Figure 63, Section 7.3), or improvement in the quality of an existing cycle route, for example by adding lighting, could be accommodated by adjusting the weighting factor for this route. As such it can be concluded that the spatial analysis model provides the functional platform to investigate the effectiveness of cycle network provisions which would shift routes up the cycle route hierarchy on a city wide or sub-area basis with relatively little time and resource input.

Although at present the accuracy of the modelling approach for cyclist flows cannot be validated due to lack of available cyclist flow monitoring data, the methodology to undertake this validation would be as demonstrated for the vehicle traffic model implemented within this thesis. The application of the space analysis modelling approach described above to city wide cycling networks addresses a number of shortcomings of the existing body of research undertaken in this field. For example, Cahill and Garrick (2008) concluded from their limited study that space syntax was potentially well suited to bicycle network planning. They did suggest that large variations in quality across the network may necessitate the need for additional ‘weighting’ data to improve the models performance and that this should be supported by modelling in a selection of urban areas to validate the approach further, however their study stopped short of developing such weighting methods. Iacono (2010) provided guidance on measuring non-motorised accessibility and suggested that information required to comprehensively undertake such research included:

- travel survey data to provide travel behavioural information;
- detailed land use data at high resolution;
- GIS layers to represent travel networks and non-motorised infrastructure;

- identification of impedance functions for non-motorised modes and destination types using time and distance from different sources.

The combination of the spatial analysis model and questionnaire undertaken in this thesis provided solutions, at least in part, to each of these points. Spatial analysis modelling provides a unique opportunity for modelling accessibility for cyclists in that it allows cycling networks to be presented at an urban scale whilst considering every route within the network. Typical modelling networks are coarse, following cyclist paths only, or data is aggregated within zones which can be too large to allow representation of short trips (Iacono, 2010). Cycle trips can often be short enough to take place within one zone on a more traditional model which would therefore exclude the trip from being recorded (Berrigan et al., 2008). The spatial analysis of cycle networks demonstrated in this thesis represents all elements of the cycle infrastructure including dedicated cycle paths and lanes, recommended routes, or roads with no specific cycling provisions, and as such addresses the modelling limitations described by Iacono (2010) and Berrigan et al. (2008).

At present the main limitation for further development and application of the spatial analysis model for cycling networks is a lack of available data to fully validate the model for cycling flows. However, the research undertaken has demonstrated that space analysis modelling is a valid approach to investigating the development and modification of cycling infrastructure at an urban scale.

10.3 The potential for combined motor traffic and cycle urban scale spatial analysis modelling

The spatial analysis model has been used to demonstrate the potential to investigate how relative flows of both cyclists and motor traffic are affected by the possible modification of

infrastructure for each mode. Results indicated that when an individual road with moderate connectivity was removed from the motor traffic network and was therefore no longer available for vehicular traffic, the *relative* integration values of adjacent routes increased which, based on the results of the validation of the motor traffic flow model described above indicates that increased levels of motor traffic were likely to occur on adjacent roads. The model therefore predicted that removal of availability of this road forced motor traffic to take adjacent alternative routes to reach their destination.

An assessment was also made of the impact that this road closure may have on relative cycle flows. Route weighting factors were used within the cycle network integration map to increase the appeal to cyclists of the road closed to vehicular traffic. Following weighting the integration map indicated a significant shift of relative cycle flows onto the motor traffic free route (Figure 62, Section 7.3). The result shows that making a key core route motor traffic free had more of an impact on the shift of cycle flow than by increasing connectivity on minor routes (Figure 63, Section 7.3). These hypothetical examples indicate that one major infrastructure change for both motor traffic and cyclists could potentially provide a better investment opportunity than making numerous small connection changes. However, the level of financial investment associated with these changes would obviously have to be considered. The spatial analysis model could be used to investigate the difference in impact of making connections between existing major cycle routes and comparing these with an alternative scenario of building a new off road cycle path. This demonstrates how the spatial analysis model could be applied in a real world situation where local authorities have limited budgets to spend on improving cycle networks and have to make choices between different options. The impact of making numerous small connections within a larger cycling (and motor traffic) network can be investigated using the model, allowing investment to be targeted to where it is likely to be most effective.

The ability of the spatial analysis model to investigate the impacts of modifications to the transport network for both motor traffic and cycle flows is potentially extremely useful, particularly at the early planning/scoping stage. For example, the model could be used to assess the positive/negative impacts on both motor traffic and cycle flows when closing a series of city centre roads to vehicles, or incorporating a dedicated cycle lane by reducing road width to vehicles, which could be represented through a reduction in the weighting factor within the motor traffic flow model i.e. making the road less attractive for vehicular traffic. The demonstration indicates that not only is the model capable of assessing the relative flows along the routes directly affected by the changes, but that it can also represent changes to flows in adjacent roads and areas caused as a result of diverted motor traffic or as a result of the route becoming more, or less, favourable. Whilst the review of literature in the area has identified the use of space syntax to model motor traffic flow, and limited research on using space syntax to model cyclist flows, the author is not aware of any space syntax based models capable of representing the interaction between each in this manner.

It can therefore be concluded that the model is capable of representing the potential interaction between motor traffic and cycle networks, although the axial maps have to be represented, modified and modelled in different layers in GIS at present. Recording and analysing existing cycling and motor traffic infrastructure within one platform would be beneficial to the overall planning process. The combined GIS model could be used as a collaborative method for sharing data including cycle flows, motor traffic hotspot data and other relevant information for cyclists such as accident rates. The overall model would be a useful tool as the impact of changes to both networks can be modified quickly and different options can be run to identify where changes will have least/most impact depending on the change required, and there is a

significantly reduced data requirement to achieve this compared to conventional transport models.

10.4 Investigation of individual cycle routes using the spatial analysis model and factors influencing individual route choice

Being able to identify choices made by individual cyclists would be a very useful modelling feature, for example to improve facilities available in areas of potential high modal shift and to reduce the need for real flow data. The spatial analysis model was not specifically designed to predict the routes of individual journeys, however, an assessment of the model's ability to predict individual journeys was made to investigate whether it is a realistic goal to use a space syntax based model in this way at a city/regional scale. Section 9.2 describes the results gained when the model was used to compare model predicted and actual routes taken by individual cyclists. The model was used to predict the most direct route between the start and end point for journeys made by cyclists who believed that they completed the journey using the most direct available route. Results showed that only 25% of the journey taken by cyclists accurately matched in their entirety the most direct route calculated by the model (Table 17, Section 9.2). This indicates that although a large proportion of cyclists believe they choose the most direct route this does not appear to be the case for 75% of the sample. It was found that the model was less reliable in predicting journeys along off-road cycle routes. Off-road routes are often less direct than other possible routes along roads, and can include more changes in direction which creates less integrated routes as identified by spatial analysis procedures. From these findings, together with detailed comparisons of the time spent on different routes between actual and predicted journeys (Table 18, Section 9.2), it can be concluded that even when cyclists believe they take the most direct route to complete their journey, in the majority of cases they do modify their journey to use additional cycling facilities such as on-road lanes and off-road paths, or to avoid particular areas perceived to be less favourable for cyclists,

such as busy junctions. This provides additional support for the route weighting method for the cycling integration map and particularly the shift in relative flows when isolated key routes are closed to motor traffic as illustrated above.

Of the sample surveyed, 75% of those who believed that they took the most direct available route in fact did not. This result highlights a problem that can only be partially addressed using the route weighting facility previously described and presents a potentially significant problem when trying to predict specific routes taken by individual cyclists. Any model that aims to predict individual cyclist movements needs to incorporate a greater understanding of the factors that, either consciously or sub-consciously, affect choices made by cyclists when selecting their journey route. A greater understanding of cyclist behaviour and factors that impact on this behaviour is therefore required.

A questionnaire was distributed and analysed to attempt to understand cyclist behaviour and to evaluate the use of existing cycle networks including why people make the choices that they do when cycling, and to identify the relative importance of different factors in the decision to undertake a journey to work by bicycle or other means. The results provided insights into factors that could be used to encourage more people to cycle to work and could inform future efforts to model cyclist journey routes. Responses to the questionnaire provided evidence that the distance travelled by cyclists provided significant scope for increasing modal shift, with over 80% reporting that they travel less than 5 miles to work which is considered a reasonable distance to travel, with 64% of the population travelling less than 10km (6.2 miles) to work in the UK (ONS, 2014). This was supported by respondents confirming that 76% of journey times by bicycle take less than 30 minutes compared to 61% of journeys by other alternative modes, illustrating that there was a time benefit, or at least a perceived time benefit, when

travelling short distances by bicycle. These results provided support that there is potential for modal shift if appropriate cycle facilities are located in high impact locations.

Only 35% of respondents stated that a shorter route to work was important in making the decision to cycle to work. Therefore 65% of respondents would be prepared to increase the route length to deviate to a more attractive, safer route. This provided further weight to the modelling evidence described in the previous section that identified that 75% of respondents who believed that they cycled along the shortest available route did not in fact do so. Tilahun et al (2007) found that cyclists were prepared to cycle longer distances to avoid unsafe routes. 80% of respondents agreed that safer routes would encourage them to cycle more often. Jones (2012) reached the conclusion that proximity to motor traffic free facilities appeared to increase awareness of opportunities for traffic free cycling but found that levels of cycling had not increased since the traffic-free intervention had been completed.

Exposure to motor traffic was found to be a key factor that influenced the route taken to work by bicycle. This was supported by 90% of respondents feeling that they were at 'moderate' or 'much' risk from cars and vans during their journey, with dangerous junctions perceived as the second highest risk. Risk related factors have a strong bearing on route choice and it has been found that reductions in risk are highly valued by cyclists (Hopkinson et al, 1996). Hopkinson (1996) found that significant reductions in risk were more achievable than large time savings and it was contended that reducing risk was a much more important stimulus to cycling than reducing journey time. This is supported by the research undertaken in this thesis as it demonstrates that routes chosen are not necessarily the shortest. A number of options exist if trying to minimise the perceived risks associated with the interaction between cyclist and motor traffic, therefore increasing modal shift, including the complete closure of selected routes to motor traffic, reduction in motor traffic volumes, or reduction in the speed of motor

traffic. The impact of such changes could be determined at a scoping or planning stage using the space syntax model demonstrated in this thesis.

Results from Categorical Regression Analysis (Section 9.3.6) indicated that there were more opportunities related to route characteristics that could be influenced by infrastructure changes for occasional cyclists than for frequent/everyday cyclists. Average journey time, time spent on quiet roads and lack of dedicated cycle lanes were found to have the strongest influence on this group compared with other cyclists, and as such route infrastructure modifications and connectivity improvement particularly could have a greater impact on modal shift within this group who have greater scope to cycle more often. Categorical Regression Analysis indicated that not all cyclists had similar feelings about the problems and benefits associated with cycling, and this may have implications on targeting facilities and policies. The analysis demonstrated that it is important to understand more about what motivates different groups of the population for different modes. Those who are willing to cycle are not a homogenous group (Gatersleben and Appleton, 2006) and as such diverse packages of measures rather than one option are likely to be more successful in increasing cycling levels.

The questionnaire survey was very much designed to gather basic behavioural information. Having completed this thesis, it is clear that further information would be of benefit, particularly when further developing the route weighting methodology during any future validation of the cycling model. The collection of further information on preference towards different cycling facilities would be beneficial, for example, on-road/off road facilities and what specific infrastructure features on their route to work encourage or discourage to choose a particular route, for example, number of traffic lights, parked cars or pleasant scenery. In addition to a more specific survey of infrastructure preferences, a greater understanding of the motivational triggers which might lead to modal shift would be beneficial. Spatial variations

in the decision to cycle including psychological, cultural and social factors together with environmental influences such as land use mix and existing transport systems (Jones, 2012) means there is a need to broaden the depth of analysis to include both the physical environment and the psycho, cultural and social aspects. Behavioural assumptions are often borrowed from research focussing on other areas which may be sensitive to contextual conditions, particularly weather conditions (Iacono et al., 2010). These have been acknowledged within this research to some extent through the inclusion of three UK cities with different contextual situations.

The response rate of survey was relatively high with targeting of cyclists at their place of work being particularly successful and the data gathered therefore contributes to current literature on route choice and cyclist behaviour. The sample size and questions were limited due to time and financial constraints of the project but were adequate for the level of analysis required. With regards to inclusion of the map for the identification of stated preference of route within the survey there is some question over the reliability of the results, particularly as such a high proportion of respondents believed they took the shortest route. Even though accuracy of predicting individual route choices could be questioned, this exercise did reveal an interesting insight into the perceptions of cyclists and the routes that they take. The fact that a large proportion of the respondents believed that they took the most direct route, even though the majority in fact did not, suggests that there is a high degree of either conscious or sub-conscious route modification taking place amongst cyclists. Care needs to be taken with the ability of respondents to complete the survey in the way expected. It has been suggested that the more information provided to the respondent regarding the aim of the survey the more statistically relevant the results will be (Rose and Bliemer, 2008). Stinson and Bhat (2003) and Ortuzar and Willumsen (2001) highlight the importance of the timing of such as survey noting that responses can be very different at different times of the year, therefore travel data should be collected all year round. Stinson and Bhat (2003) found that responses during the summer

were focussed more on the built environment whilst in the spring more emphasis was placed on the weather. Therefore biannual surveys may obtain a more balanced set of results.

10.5 Benefits and shortcomings of the spatial analysis model

It can be difficult and costly to obtain the volume and detailed level of data that is necessary to allow accurate predictions to be made by a model. The time and the data needs required to 'build' an axial map is small compared to typical transport models (Barros et al, 2007), and this represents a real benefit to potential users of the technique. Ratti (2005) suggested that an increase in the ability of computer techniques and resources would enhance the ability to explore urban texture. However, this development in technology needs to be supported by the availability of real data to calibrate and validate models and to provide a better understanding of conditions encountered (Antoniou et al., 2014). An increase in computational power cannot replace a minimum baseline of data on which the model must be validated. Most traditional transportation models are based on large volumes of origin and destination data that also require detailed data on trips, but this collection of data for a specific location is rarely repeated (Cahill and Garrick, 2008). As indicated by Cahill and Garrick (2008) and from motor traffic validation work undertaken in this study, data collection points should be located on a broad range of routes and at appropriate locations which provide an extensive data set that could be used to correlate with data obtained from the integration maps and transport models in general. Research in this thesis has demonstrated, through the validation of the motor traffic flow model, that relatively accurate predictions can be achieved using a limited amount of data from a broad range of data points consistent with routine motor traffic modelling undertaken by local authorities across the UK. If the same level of data could be collected for cyclists, the model could be tested and validated in the same way. However, the level of data available to undertake this validation within this thesis was not available.

As described in Section 5.2, the space analysis model struggled to produce good correlations with motor traffic flow data where motor traffic flow levels were relatively low. The low number of journeys along relatively poorly connected routes are likely to be associated with the beginning or end of specific journeys, and the effects of personal route choice become more dominant as the dispersal effect associated with higher motor traffic flows becomes less influential. As such, these journeys become harder to predict with accuracy using the existing model. However, as motor traffic flows are low, the impact on the overall accuracy of the model is proportionally low, with the majority of modelled motor traffic flows correlating well with measured traffic flows. Future research could be directed at improving the method for low flows, however, there will be a diminishing return in terms of the additional effort required and the corresponding increase in overall model accuracy at an urban scale.

Limitations exist associated with the transferability of models and data between countries, for example, the transfer of the model QUOVADIS-BIKE established in the Netherlands based on the Dutch cycling culture, which did not transfer well to the UK which has a much lower modal share of cyclists (Cahill and Garrick, 2008). In the UK, Europe and the US basic information to implement the spatial analysis model is generally available, however results may not be transferable to other parts of the world where appropriate software, basic GIS maps and flow data are not available. This thesis has demonstrated through the incorporation of six UK cities/regions that there is potential for replication across the UK and to other countries where similar data sets are available.

Chen (2008) found that the journey to work is complex, combining a number of activities and that the complexity of journey influences mode choice. A broad set of issues that have been shown to impact on route choice including aesthetics, quality of routes etc. are difficult to

incorporate into spatial analysis modelling as they 1) vary along axial line, 2) vary on a short term temporal basis 3) are subjective (Ratti, 2004). As the aim of this model was to provide an urban scale model designed for the initial planning stage the necessity to include these highly variable features was considered to be outside of the scope of the current research. The large data volumes associated with more traditional, detailed models would arguably allow for at least the partial inclusion of such factors when detailed investigations are undertaken following this initial scoping stage.

As with all modelling, opportunities for error exist at different stages of the process, for example, during collection and analysis of data and the creation of axial maps or may be inherent within the process due to variable data availability for different time periods and over different spatial scales and places. Ratti (2004) criticised space syntax stating that small configuration changes, implemented through human interpretation, were found to be significant for small spaces and could impact on the representation. This is likely to be diluted on urban scale, although further evidence is required to support this.

Practitioners are primarily looking for improvements to conventional models to answer existing questions (McNally and Rindt, 2008) rather than develop additional skills using new models. The spatial analysis model uses a commonly used GIS package, MapInfo, and Ordnance Survey maps which would be familiar to a technician involved within the planning process within a range of sectors within a local authority. Cahill and Garrick (2008) stated that creating axial maps for extensive networks can be an 'arduous' task. However, the process of creating an axial map at a city wide scale is generally a desk top exercise, particularly with the availability of online mapping facilities such as Googlemaps. It is estimated that an urban scale network for a typical UK city may take two to three weeks to create by someone with basic MapInfo experience and an understanding of the city under investigation. However, once the

baseline map is created, updating the axial map with new or modified roads or routes takes a few minutes by adding or removing axial lines, or potentially by modifying weighting factors. Overall, a balance needs to be reached between accuracy and time involved in creating axial maps and spatial analysis models as a whole. Further work could be undertaken to analyse the difference in interpretation of spaces between experts, including how they are modelled using space syntax and also create clearly defined criteria wherever possible to remove the potential for uncertainty.

The ability to represent movement in and out of a space has been alluded to within previous space syntax research, particularly on an urban scale. In an analysis of small urban areas Ratti (2005) used some selection of boundaries but the methods used were not explained. Ratti (2005) went on to say that a more precise method of weighting could occur during the integration process which includes a decay function to represent adjacent urban spaces. The methodology presented in this thesis includes such a boundary weighting through the incorporation of connections and levels at classified locations at the boundary of both a sub-area and city scale. This weighting method was successful at the sub-urban scale, providing strong correlations between integration values and motor traffic flow figures. At the city scale the correlation was not as successful, partially due to the limited impact of the edge effect on such a large axial map, and partially due to potential limitations with the number of connections and levels within the spatial analysis model that has been developed. Future development of the space analysis methodology should include a re-evaluation of the algorithms within the spatial analysis model to allow a higher number of connections and levels, as this is likely to enhance the potential for the boundary weighting to be successful at the city/region scale.

10.6 Potential application of the spatial analysis model

Typical motor traffic models require vast amount of data and preparation time whereas space syntax requires only a validated configurational map (Barros, Silva, and Holanda, 2007) as described within this thesis. Hensher and Button (2008) stated that many models are static and that they do not consider the knock on effect between periods. This spatial analysis model is iterative in that any changes made to the axial map can be used in all future calculations unless they are removed and the model is re-run. The model is therefore relatively simple to produce and flexible enough to incorporate planned modifications to the infrastructure and is therefore considered as an ideal platform on which to investigate the impacts and effectiveness of various transport network options at a scoping stage. However, as with any iterative process model parameters need to be supported by long term studies to ensure that changes are reflected within the model.

The model could be used to demonstrate any future changes to the connectivity of the motor traffic and cycle network. For example, it could be used to investigate the addition of a new mixed use estate developed at the edge of a city and the impact that this might have on movement patterns within both the local and broader urban area. This approach has been tested in the area of Brøset in Norway by Manum and Nordstrom (2013) using the Place Syntax tool for pedestrians where accessibility mapping has been used to look at accessibility to schools. Basic investigations found that schools were poorly accessible in the area of Brøset and that this should be improved to encourage a 'carbon neutral settlement'. Button and Hensher (2008) pointed out that restricted access across publicly owned land such as schools and hospitals reduces connectivity in cities. By finding ways to open up these spaces without compromising on security, places can become more connected for relatively little investment and these opportunities could be investigated by the model. A recent gating policy introduced

in the UK (Clean Neighbourhoods and Environment Act, 2005) to reduce crime such as fly tipping, burglary and anti-social behaviour has reduced connectivity in urban spaces. Land ownership of lanes and alleyways together with access laws would need to be investigated but opportunities for potential increasing connectivity could be identified. However, Jones et al. (2012) has found that the common assumption that by simply providing activities close to homes along highly connected street network will encourage walking and cycling is tenuous and that increasing connectivity alone is insufficient to increase modal shift. Those who currently cycle do so regardless of urban conditions or construct their own routes to access their destination. Research by Jones et al. (2012) indicates that more attention should be given to improving the quality of main roads and junctions to increase walking and cycling.

The spatial analysis model can be linked to other models such as the Energy and Environmental Prediction (EEP) model which includes other sub-models incorporating data on buildings, health and air pollution (Jones et al., 2000; Jones et al., 2007). The motor traffic and cycle flow model could be 'plugged' into the EEP model and linked to ADMS Urban data contained within this model, allowing for associated emissions to be predicted at a postcode level. Collation with other tools such as Residential Environment Assessment Tool (REAT) which provides other measures of urban attraction is also possible which would enable a broader range of potential weighting factors to be utilised (Cardiff University, 2013).

Chapter 11: Conclusions

11.1 Conclusions

The aim of this study was to investigate the potential to model motor traffic and cycle flow at an urban scale using spatial analysis techniques so as to identify routes within a city that could be targeted to improve accessibility for cyclists, therefore encouraging modal shift. The conclusions of this research are presented below.

It has been found that the creation and utilisation of space analysis axial maps represent a time and resource efficient, flexible approach for representing a complex transport network at an urban scale. The basic axial map of an entire road network for a city can provide the basis for a range of possible modelling tasks, which can be assembled by a non-traffic modelling expert within 2-3 weeks using commonly used IT and mapping resources.

Identify, test and improve the spatial analysis model for aggregated motor traffic flow at an urban scale

A review of potentially useful modelling approaches was undertaken to identify a suitable spatial analysis model that quantifies relative levels of motor traffic flow for an entire road system for a city or region, including both local and strategic roads, that requires as little data as possible, whilst providing meaningful and useful outputs. Space syntax was selected as an appropriate approach based in the commonly used GIS MapInfo.

During the testing process it was identified that the most basic motor traffic flow data available was not sufficient to validate the motor traffic flow spatial analysis model, principally because the dataset itself was limited it did not represent the full range of road types and motor traffic flows that would be expected within an urban environment. As such a greater level of motor

traffic flow data was required in order to validate the space analysis model for motor traffic flow.

An increased data set to represent a wider range of motor traffic flows and road types greatly improved the correlation between motor traffic flow data and integration values when non-isolated areas were considered. However, when areas were treated in isolation the ‘edge effect’ created when the model did not allow for motor traffic crossing the boundary of the modelled area dominated model calculations to the extent that this improvement in model correlation due to the improved dataset was no longer evident. Therefore a method of compensating for edge effect was required to allow for motor traffic entering and leaving the modelled area, with the aim of further improving the correlation.

Radius integration that allowed local movements to be reflected in the integration values resulted in the correlation between average hourly traffic flow and radius integration calculations being weaker than the global integration calculations used in the standard space syntax model. This was true both for level 3 and level 7 radius integration. Whilst it is possible that utilising much higher levels for radius integration may have improved the performance of the method, this would negate the value of the method in representing more local movements. Radius integration was therefore not considered an appropriate method for modelling transport networks at an urban scale.

Boundary weighting, when considering smaller, isolated areas, was demonstrated as a valid means of representing the movement of motor traffic across the area boundary and can be applied when modelling small sub areas of the urban environment where there is little or no data for the area outside that being modelled. However, correlations between integration values and motor traffic flow were only marginally improved at a city scale when boundary

weightings were applied, and it can therefore be concluded that currently the additional effort of undertaking the boundary weighting methodology cannot be justified by the small improvement in correlation values obtained when considering the city wide area.

Road weighting, based on national road classification, has been demonstrated as an effective weighting methodology at a city/region scale and allows the model to represent higher motor traffic flows on routes that are designed to carry higher motor traffic loads and are therefore more attractive to drivers. The relatively simple classification upon which the best performing road weighting method is based meets with the overall model aim of being relatively straightforward to implement. In theory, it would be possible to represent other specific features that encourage or discourage motor traffic flows, however, this would require significantly more data to be collected, which may not be practicable at an urban scale, and would require that the model is updated on a regular basis to reflect minor infrastructure changes.

By applying the space analysis modelling methodology and the weighting methods developed to other urban areas, it has been demonstrated that they are transferable to other urban areas and can be implemented using readily available levels of aggregated motor traffic flow data. This therefore satisfies one of the initial objectives of the model.

Evaluate the potential for transferability of the spatial analysis model for aggregated cycle flow and motor traffic flow

Relatively minor modifications to the spatial analysis model can be made to include additional routes available to cyclists, such as off road cycle paths, routes through open spaces, or links between 'dead end' roads. The space syntax method can therefore provide a functional platform to investigate the existing or potential utilisation and effectiveness of cycle network

provisions which can demonstrate the shift of selected routes up the cycle route hierarchy on a city wide or sub-area basis with relatively little time and resource input compared to traditional transport modelling techniques.

Identify the potential for the model to illustrate the impact of change in infrastructure on relative flow of motor traffic and cyclists

A single spatial analysis model is capable of representing the potential interaction between motor traffic and cycle networks, although the axial maps have to be represented, modified and modelled in different layers in GIS at present. Recording and analysing existing cycling and motor traffic infrastructure within one platform would be beneficial to the overall planning process and the combined GIS model could be used as collaborative method for sharing data including cycle flows, motor traffic hotspot data and other relevant information for cyclists such as accident rates. The overall model would be a useful tool as the impact of changes to both networks can be modified quickly and different options can be run to identify where changes will have least/most impact depending on the change required, and there is a significantly reduced data requirement to achieve this compared to conventional transport models.

Identify whether individual cyclist movement can be predicted by the model

Investigations of the routes travelled by individual cyclists indicated that, even when cyclists believe they take the most direct route to complete their journey, in the majority of cases the route taken does not correspond to the most direct route calculated by the model. Whilst this indicates that the modelling method is not appropriate for predicting individual routes, it does provide the useful conclusion that cyclists do modify their journey to use additional cycling facilities such as on-road lanes and off-road paths, or to avoid particular areas perceived to be less favourable for cyclists, such as busy junctions. Further, detailed investigation of cyclist

behaviour is required to fully understand the mechanism through which cyclists choose the specific routes taken on routine journeys.

Investigate the factors that influence cyclist behaviour to evaluate use of existing cycle networks

Analysis of the factors that influence different groups of cyclists suggest that different factors influence them to cycle. Results indicate that there were more opportunities related to route characteristics that could be influenced by infrastructure changes for occasional cyclists than for frequent/everyday cyclists. This is the group that have more capacity for modal shift and are likely to share similar feelings to non-cyclists who may consider utilising a bicycle for their journey to work. Average journey time, time spent on quiet roads and lack of dedicated cycle lanes were found to have the strongest influence on occasional cyclists, and as such route infrastructure modifications and connectivity improvements could have a greater impact on modal shift.

Spatial analysis modelling at an urban scale

The thesis has tested a software package for applications that it has not been used for previously and validates the software against measured data for motor traffic and against another traffic model. The space syntax modelling technique used was novel in that it is based within a commonly used Geographical Information System (GIS) desktop software, MapInfo . This software package is relatively easy to use, is capable of storing data for all roads on a city or regional scale, data can be displayed as a spreadsheet or in map form enabling clear visualisation of results, is familiar to many local authorities in the UK who are the main potential users of the model and is relatively cheap to purchase and can be used on any PC of standard specification, therefore providing significant support for a the requirements of the research to provide a reliable scoping modelling.

It has investigated the use of a spatial analysis model to predict motor traffic flow with a relative degree of accuracy (comparable to other modelling approaches) when all roads within a network are considered and has tested the development of boundary and road weighting techniques at a city/region wide scale. The research has shown that the road weighting method was found to be the most effective at improving the performance of the model at city/regional scale for replicating aggregated motor traffic flow. This has been highlighted as the preferred method that is transferable to other cities and has demonstrated for four UK city/regions based on data from a broad range of road types.

The method tested enables reliable real motor traffic flow predictions to be made quickly for every road within a city and could therefore be used as a relatively quick to use tool to investigate changes to the network layout. Therefore a novel, data efficient approach to modelling relative motor traffic flow on an urban scale has been demonstrated and validated in this thesis. The spatial analysis model is not intended to replace traditional traffic flow models such as SATURN as they generate outputs that have different uses, but can be used as a precursor to test potential scenarios. It can be used as a tool to test the impact of potential infrastructure changes on motor traffic flow with a relatively high degree of accuracy, using commonly used software and short computational times predicting flow on all roads in a city/region. By combining the motor traffic and cycling models into a common spatial analysis model, networks could be designed to incorporate bicycle use more effectively. In traditional travel demand models, the share of bicycle trips is very small and so is often ignored. However, the implication of cycle infrastructure is significant on transportation planning and without its incorporation into a more holistic planning approach, cycling as a viable mode will not increase significantly. The opportunity to include both motor traffic flow and cycling modelling at an urban scale within the space analysis model could provide a way forward for this.

11.2 Future research and recommendations

As a result of the research undertaken within this thesis a number of suggestions are made for future research.

Whilst it is difficult to accurately monitor cycle flow rates across a wide range of network routes, further research into low cost methods to accurately record cyclist movements across the network should be undertaken. It was not possible to validate the cycling model within this study as cycle flow rate data was not available for either dedicated cycling infrastructure such as off road tracks, or on the general road network. This data would be valuable in determining baseline cycling levels prior to infrastructure changes, and would allow the validation of models such as that developed in this thesis.

Many assumptions are made during basic space syntax procedures as all space is treated as equal, for example, gradient, quality of surface, on-road parking and safety issues are not taken into account. At present, weighting factors investigated within this thesis, including the most effective method of road weighting, is only capable of accounting for road characteristics that are fairly consistent through time and across space. In reality, however, the factors that could potentially affect motor traffic flow may vary over short time periods or over small distances, such as the reduction in useable road width and on-street parking and other temporal variations and their impact on bicycle usage and safety considerations (Stener et al, 2009). Modifications to the weighting factors would be required to enable different temporal or small scale spatial changes to be accommodated within the model. However, at an urban scale, although valuable, this would be difficult and time consuming to collate appropriate information whilst maintaining unambiguous, quantitative methods for collation and replicability in other geographical areas. Further research into the potential of incorporating this fine detail without

adding significantly to the data collection process may improve flow predictions at this finer level.

The model was limited in its ability to predict motor traffic flows on minor roads with relatively low vehicle movements, primarily because these journeys are more origin/destination orientated, subject to greater influence of personal choice and with less opportunity for these effects to be averaged out with higher motor traffic flow. Whilst the effect was not significant at an urban scale, it could be significant if the model were to be used to investigate an urban area dominated by low motor traffic flows. Further research into methods to more accurately accommodate these low flows into the model should be undertaken.

The spatial analysis model could be linked to other urban scale modelling tools designed for collecting other relevant data such as the Residential Environment Assessment Tool (REAT) which captures contextual data on the quality of the built environment (Cardiff University 2013; Dunstan et al., 2013; Thomas et al., 2007). This tool collects neighbourhood attractiveness data at a postcode level for factors such as natural elements, defensible space, territorial functioning and physical incivilities, some of which are relevant issues that could be considered attractive or unattractive to cyclists on their chosen route to work. These characteristics could be used as weighting factors if collected for every space within the urban environment. However, if data is not available to weight every axial line, the data would not be able to be used as weightings would not be comparable. Further research into how the space analysis model developed could be integrated with other models could result in greater overall value being achieved.

The 'install it and leave it' approach should not be taken when developing cycling networks. Some pre-test and post-test experimental design to evaluate the impact of interventions which

target utilitarian cycling would provide evidence to the impact of a change in accessibility on the use of bicycle for commuting (Handy, 2005).

Whilst this thesis has identified the broad factors that affect some of the choices that cyclists make, this is a complex research area that warrants further work as ultimately, it is only through understanding and influencing these decisions that modal shift on a significant scale can be achieved. Further survey work could include a longitudinal study of the same sample of respondents to illustrate travel behaviour and attitudes over time as previous response rates were high and the survey was not too onerous whilst obtaining satisfactory levels of information. This type of study has been advocated for transportation studies by (Kitamura, 2008) who states that direct change can be observed, together with opportunities for coherent forecasting and dynamics in travel behaviour. Future surveys could be web-based allowing for faster data collection and processing and mappable data to be directly linked to online maps. New technologies such as Global Positioning Systems (GPS) have been used for a number of studies to monitor accurately routes taken such as Broach et al. (2010) and McNally and Rindt (2008). The equipment required tends to be expensive which would limit numbers that would be included within any future survey work.

There is a general lack of valuation studies in the built environment as a whole and particularly a lack of attention to the appraisal of cycle facilities with investment decisions rarely based on empirical evidence. Utilisation of the model to assess connectivity of existing and planned cycle routes in cities to identify where best to allocate financial resources should be combined with financial analysis such as the model developed by Sener et al. (2009).

Accurate monitoring of cycling levels is very difficult and is very costly over urban areas. However there is a need to monitor the impact of the implementation of cycle facilities to provide evidence that the installation is having a positive impact, or if users are not satisfied,

changes that can be made to improve facilities. It is recommended that flow prediction models are not an alternative to desk top and field work but would work alongside data that can be obtained from alternative sources in order to provide as much assistance as possible in making infrastructure changes and locating facilities in the most appropriate places to achieve an increase in modal shift from car to bicycle. Engagement with cyclists is very useful; however, it is very temporal and dependent on the respondents' attitudes and the factors which influence them, which can be many and varied. It is also very time consuming. Google maps has made obtaining data from site much easier from the desk however there will always be the need for clarification of more unusual situations during a site visit. Therefore a combination of information sources is required.

Following this research it is recommended that to encourage significant modal shift motor traffic free routes should be located on routes identified to be most integrated by the spatial analysis tool. Clayton and Musselwhite (2013) confirmed that to increase cycling in the short term a focus on improving safety of the network and providing high quality cycle lanes and routes for all users should be taken. Parkin (2012) suggests that the ideal urban configuration combines reduced cycling distances which reduces physical effort whilst providing an appropriate level of safety, which includes data about the origin and the destination together with the detail on the route between them. The spatial analysis model would allow for investigation of the impact of making current key motor traffic routes cycle only. Jones (2012) has found that urban traffic-free cycle routes alone appear to be insufficient in encouraging modal shift from car to bicycle for everyday practical journeys on the existing National Cycle Network but demonstrated that there was a higher rate of cycling for all journeys in the area where the intervention had been implemented which could be attributed to a range of environmental and socio-psychological factors. Cyclists surveyed within this study were keen to see supportive on-highway measures along the existing road network which connects them

to everyday activities. Findings suggest that a co-ordinated approach to promote cycling is required which should include segregated cycle facilities along main urban street corridors to advantage cycling and reduce car convenience. Initial findings from a pre and post study following the construction of new infrastructure as part of the Connect2 initiative indicate that more connected local routes have generated new trips by Goodman, Sahiqvist and Ogilvie (2014).

An allocation of motor traffic free segregated routes for cyclists would follow the economically driven approach carried out during the 1970s in UK where city centre motor traffic routes were pedestrianised to stimulate shopping. In this case the allocation of key routes to be motor traffic free would be driven by environmental reasons.

The research within this thesis supports the recommendation that to increase cycling and walking at an urban scale integrated policy is required which should include change to the organisation of the built environment, to make access to common facilities easier by foot or bicycle (Pooley et al., 2011). It is essential that policy for encouraging modal shift is developed further in order for progress towards carbon reduction targets. Pooley et al. (2012) have argued that the overall contribution of modal shift to transport related emissions is relatively small, however gains to personal health and local environment are likely to be significant which supports a cross policy approach to the problem and are likely to have more far reaching impacts with regards to overall social, economic and environmental behaviour.

Urban design can have a significant impact on modal shift and there is a need to modify the existing urban infrastructure to encourage this modal shift. This change needs to be supported by evidence of where modifications should take place and the impact that can be expected in order to prioritise the location of bicycle features in a way that can be presented clearly to all

stakeholders, including planners and the general public. By bringing cycling and motor traffic analysis together at the planning stage a coherent set of sustainable transport recommendations for planners would be possible.

It is recommended that models need to be supported by valid and reliable data sets which are multi-disciplinary. By combining models very useful cross disciplinary tools would be produced that would enable sharing of reliable data sets. For example, data sources such as land use data, the quality of the built environment and air pollution could be linked to the model developed which would help with understanding the interactions within a city and providing a holistic tool to inform policy making. This would also remove duplication of data collection and analysis work. The combined model would allow practitioners to evaluate options for implementation of small scale infrastructure changes to increase accessibility for cyclists. The model has the potential to provide a focus for joined up thinking between sectors in local authorities.

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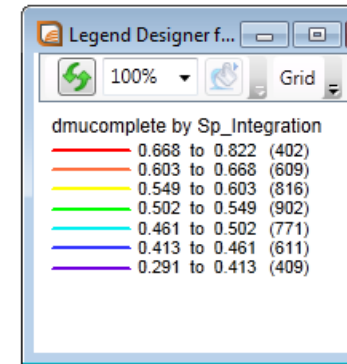
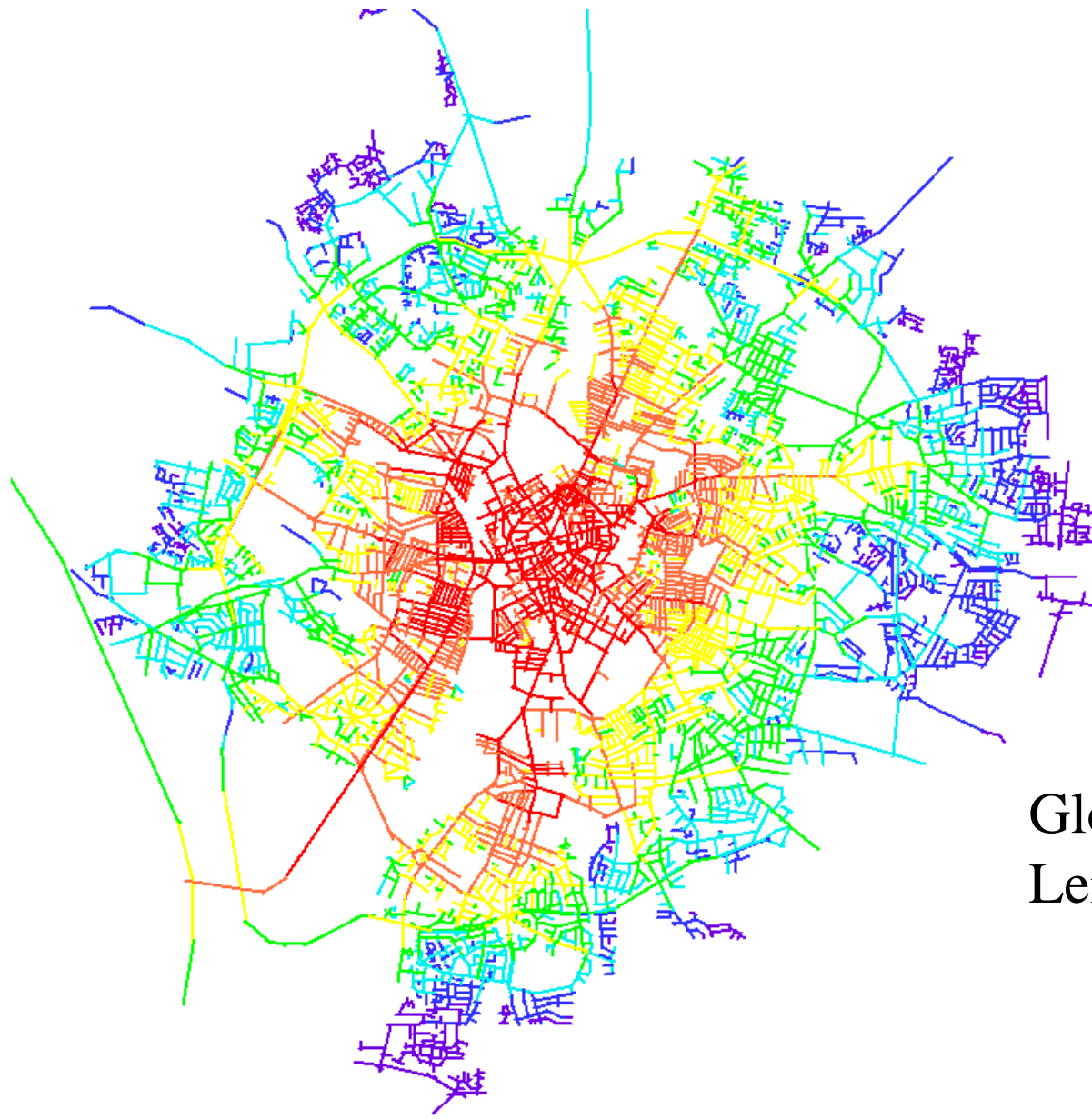
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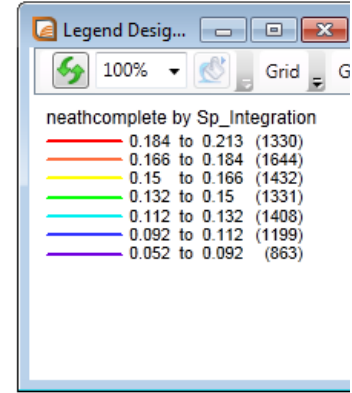
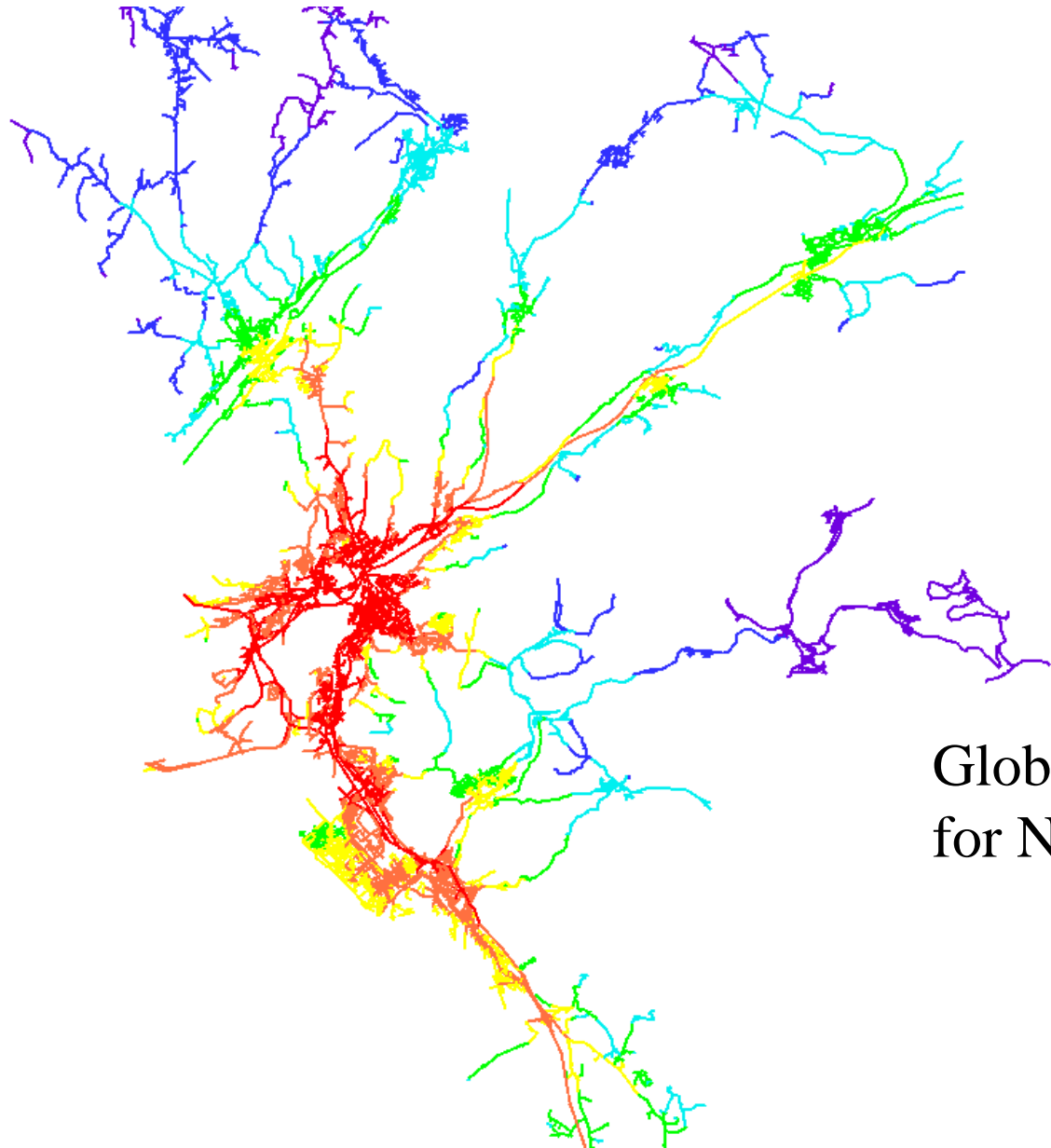
Appendices

Appendix 1

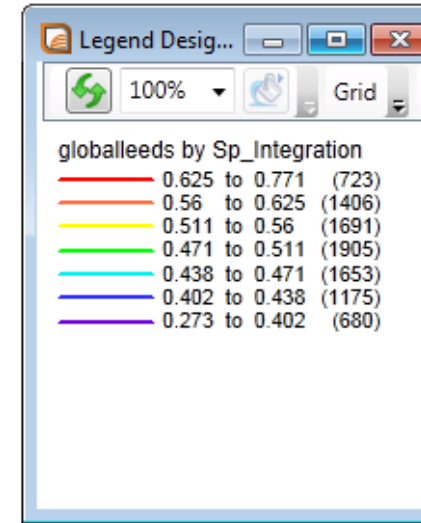
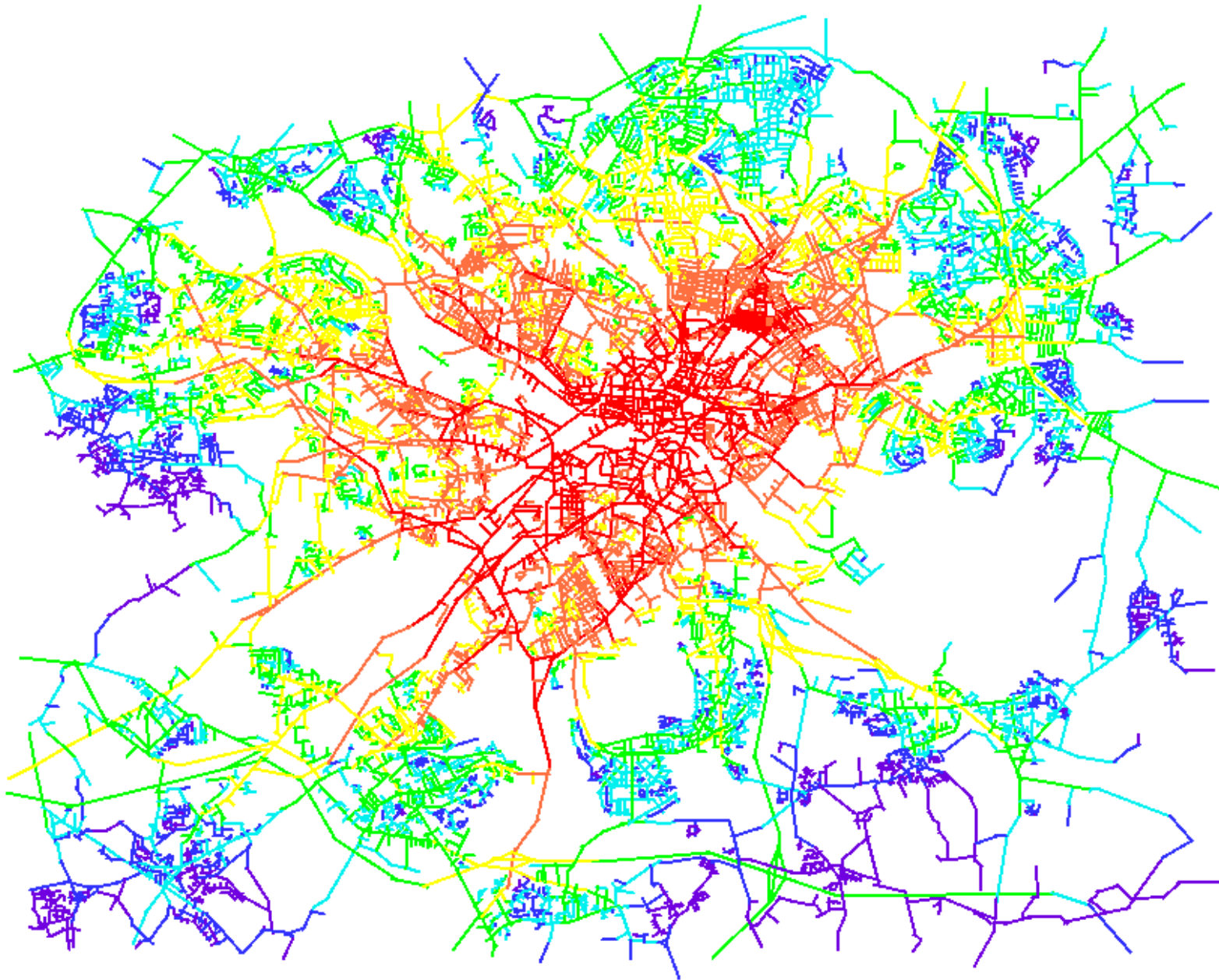
**Global integration maps for cities/regions within the validation of
traffic flow model**



Global integration map for
Leicester traffic



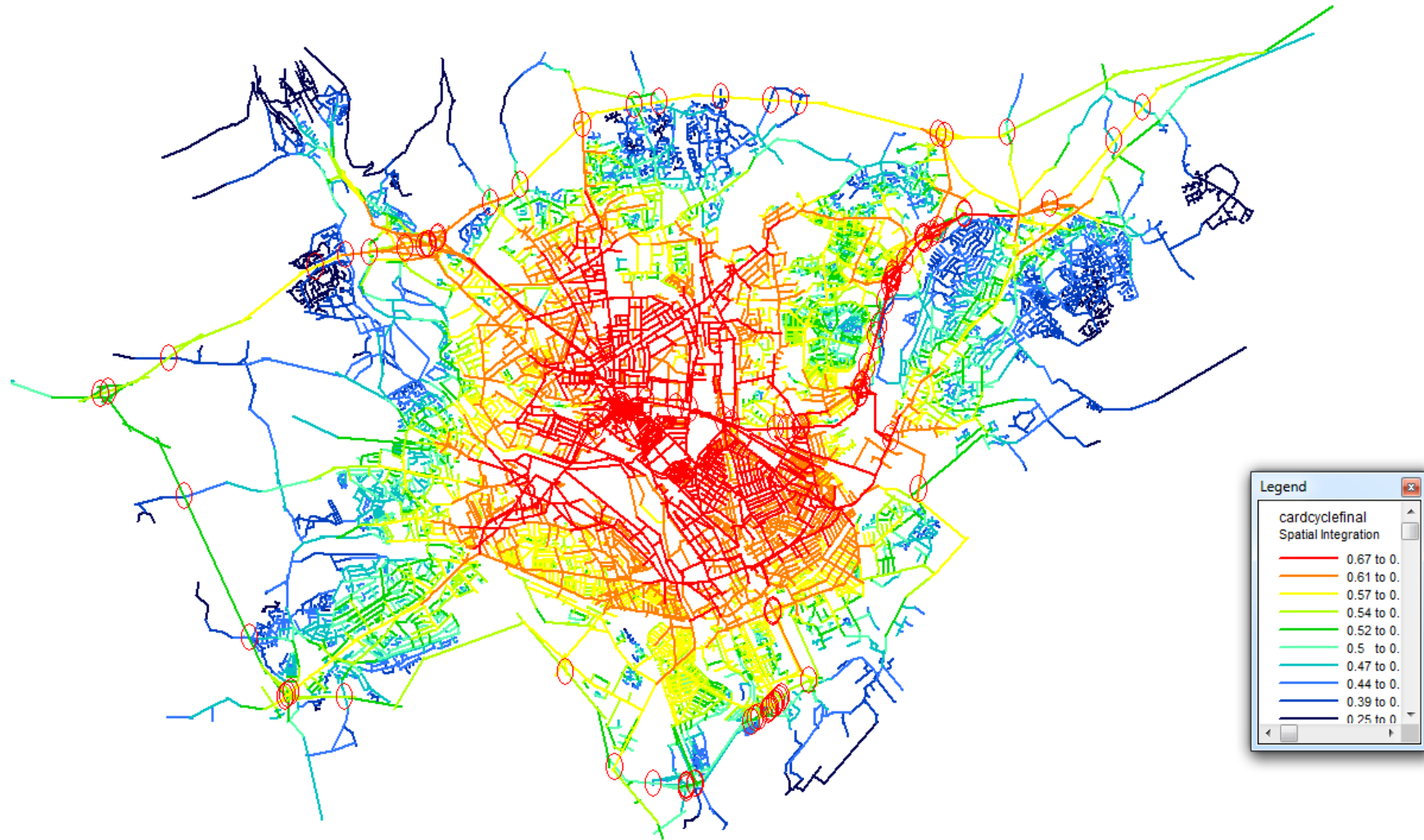
Global integration map
for NPTCBC traffic



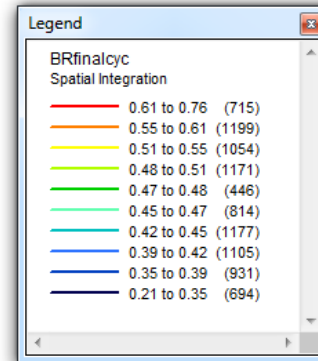
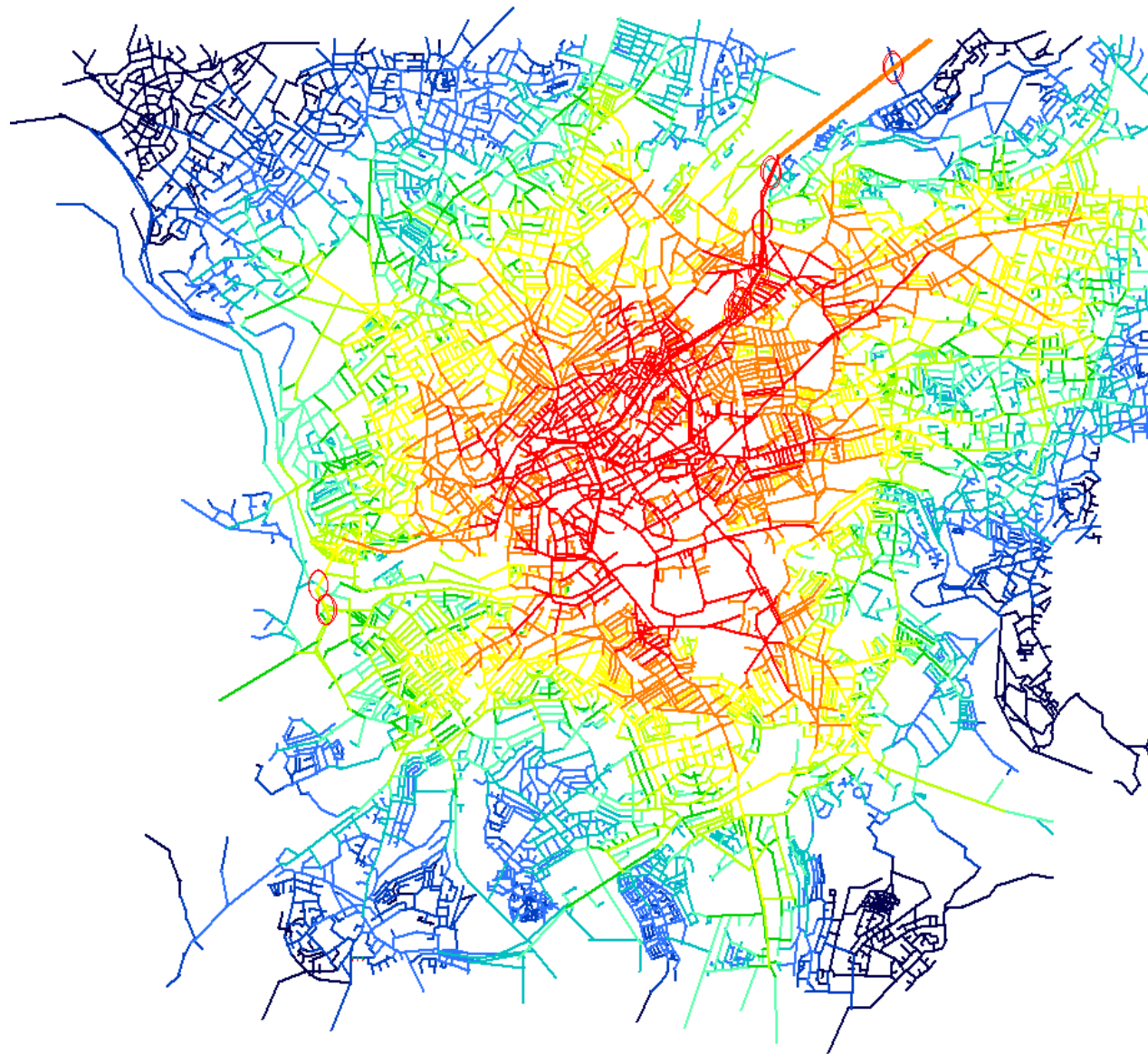
Global integration map
for Leeds traffic

Appendix 2

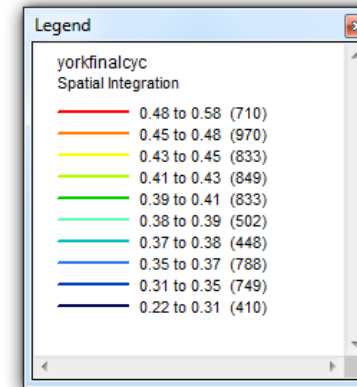
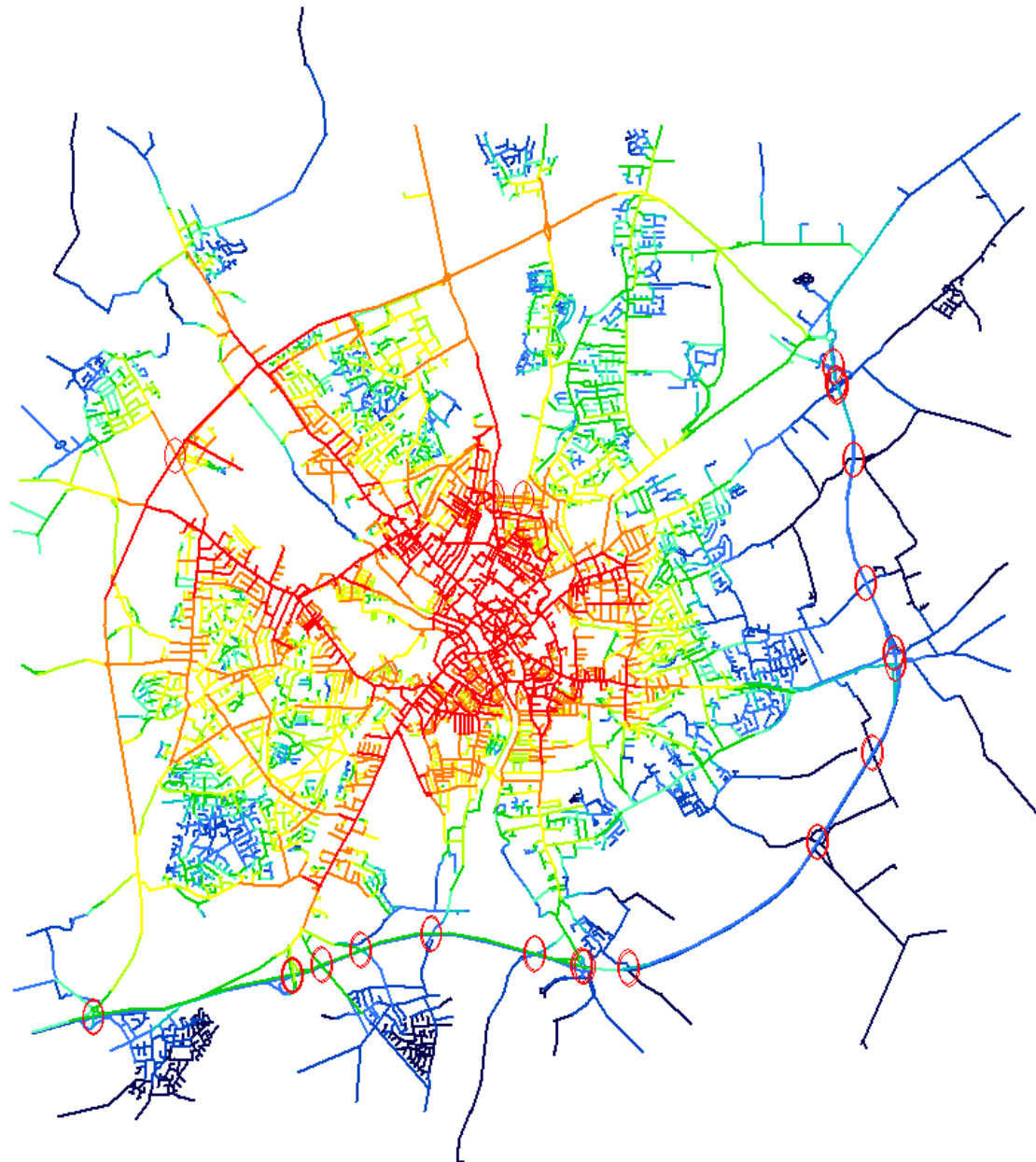
Global integration maps for cities within the cycling investigations



Global integration map for Cardiff cyclists



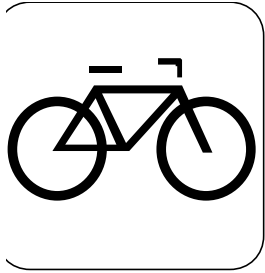
Global integration map for Bristol cyclists



Global integration map for York cyclists

Appendix 3

Cycle to work questionnaire



Do you cycle to work?

Every day? A couple of days each year?



If you cycle at all, we need your help!

**Please complete the following questionnaire.
One lucky respondent will win a quality gel saddle
worth £50!!**

Transport problems are becoming increasingly important in people's everyday lives. The problem is strongly influenced by whether people choose to travel to work by car, public transport or bicycle.

We are carrying out a research project at Cardiff University looking at what affects people's decision to cycle to work. We would therefore like people who cycle to work to complete the following simple questionnaire to help us with our work. The study will help planners and designers to improve the routes cyclists use.

Responses are very important as they may affect future policy decisions. A freepost envelope is provided to return the questionnaire.

The information that you provide will be treated in strictest confidence and will not be used for any purposes other than this research. Please let your colleagues and friends who cycle to work know about the survey. You can either photocopy the form for them or they can obtain a form using my details below.

**Please help our project be a success and be in with a chance of winning a new comfy saddle.
Fill in your questionnaire as soon as possible and return it in the freepost envelope provided.**

If you do not have an envelope you can send it to me at:

**Joanne Patterson, Welsh School of Architecture, Bute Building, Cathays Park, FREEPOST
SWC0317, CARDIFF, CF10 3NB**

**If you have any questions please do not hesitate to contact me at
e-mail Patterson@cardiff.ac.uk**

or

tel. 029 20875977



Cardiff University in collaboration with Bristol City Council, Cardiff City Council, the City Council of York, Dawes Cycles, the AA, Sustrans and Halcrow.

<p>1. Which of these best describes how often you cycle to work?</p> <p>a) In the winter (October to March)</p> <p>b) In the summer (April to September)</p>	<p style="text-align: center;"><i>Please tick one box in each line</i></p> <table style="width: 100%; border: none;"> <tr> <td style="text-align: center;">Every day</td> <td style="text-align: center;">A few days per week</td> <td style="text-align: center;">Once a week</td> <td style="text-align: center;">Less than once a week</td> </tr> <tr> <td style="text-align: center;"><input type="checkbox"/> ¹</td> <td style="text-align: center;"><input type="checkbox"/> ²</td> <td style="text-align: center;"><input type="checkbox"/> ³</td> <td style="text-align: center;"><input type="checkbox"/> ⁴</td> </tr> <tr> <td style="text-align: center;"><input type="checkbox"/> ¹</td> <td style="text-align: center;"><input type="checkbox"/> ²</td> <td style="text-align: center;"><input type="checkbox"/> ³</td> <td style="text-align: center;"><input type="checkbox"/> ⁴</td> </tr> </table>	Every day	A few days per week	Once a week	Less than once a week	<input type="checkbox"/> ¹	<input type="checkbox"/> ²	<input type="checkbox"/> ³	<input type="checkbox"/> ⁴	<input type="checkbox"/> ¹	<input type="checkbox"/> ²	<input type="checkbox"/> ³	<input type="checkbox"/> ⁴													
Every day	A few days per week	Once a week	Less than once a week																							
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<p>2. What is the usual starting point of your journey?</p>	<p style="text-align: center;"><i>Please put your answers in the boxes</i></p> <p>a) Road name <input style="width: 100%;" type="text"/></p> <p>b) Full postcode if known <input style="width: 100%;" type="text"/></p>																									
<p>3. What is the usual end point of your journey?</p>	<p style="text-align: center;"><i>Please put your answers in the boxes</i></p> <p>a) Company name <input style="width: 100%;" type="text"/></p> <p>b) Road name <input style="width: 100%;" type="text"/></p>																									
<p>4. What is the approximate distance from door to door in miles?</p>	<p style="text-align: center;"><i>Please tick one box only</i></p> <p>a) Less than 1 mile <input type="checkbox"/> ¹</p> <p>b) Between 1 and 2 miles <input type="checkbox"/> ²</p> <p>c) Between 2 and 5 miles <input type="checkbox"/> ³</p> <p>d) Between 5 and 10 miles <input type="checkbox"/> ⁴</p> <p>e) More than 10 miles <input type="checkbox"/> ⁵</p>																									
<p>5. What time do you usually start your journey?</p>	<p style="text-align: center;"><i>Please put your answer in the box</i></p> <input style="width: 100%; height: 20px;" type="text"/>																									
<p>6. What is your average journey time, in minutes, by bicycle?</p>	<p style="text-align: center;"><i>Please put your answer in the box</i></p> <input style="width: 100%; height: 20px;" type="text"/>																									
<p>7. What is your other most common mode of transport used to get to work and what is the average journey time in minutes?</p>	<p style="text-align: center;"><i>Please put your answers in the boxes</i></p> <p>a) Mode of transport <input style="width: 100%;" type="text"/></p> <p>b) Average journey time <input style="width: 100%;" type="text"/></p>																									
<p>8. Please indicate the approximate time, in minutes, that your journey by bicycle takes on the following:</p>	<p style="text-align: center;"><i>Please put your answer in all boxes that apply</i></p> <p>a) Cycle/pedestrian route (no motor traffic) <input style="width: 100%;" type="text"/> ¹</p> <p>b) Cycle/bus lane on busy road <input style="width: 100%;" type="text"/> ²</p> <p>c) Busy road with no cycling provision <input style="width: 100%;" type="text"/> ³</p> <p>d) Quiet road <input style="width: 100%;" type="text"/> ⁴</p>																									
<p>9. For your journey do you have access to:</p>	<p style="text-align: center;"><i>Please tick all that apply</i></p> <p>a) A car/van <input type="checkbox"/> ¹</p> <p>b) A motorbike/scooter/moped <input type="checkbox"/> ²</p> <p>c) A bicycle <input type="checkbox"/> ³</p> <p>d) Public transport <input type="checkbox"/> ⁴</p>																									
<p>10. In general how do you rate public transport as a means of travel to work? (<i>Please answer this question even if you do not use public transport</i>)</p>	<p style="text-align: center;"><i>Please tick one box only</i></p> <table style="width: 100%; border: none;"> <tr> <td style="text-align: center;">Very good</td> <td style="text-align: center;">Quite good</td> <td style="text-align: center;">Quite poor</td> <td style="text-align: center;">Very poor</td> </tr> <tr> <td style="text-align: center;"><input type="checkbox"/> ¹</td> <td style="text-align: center;"><input type="checkbox"/> ²</td> <td style="text-align: center;"><input type="checkbox"/> ³</td> <td style="text-align: center;"><input type="checkbox"/> ⁴</td> </tr> </table>	Very good	Quite good	Quite poor	Very poor	<input type="checkbox"/> ¹	<input type="checkbox"/> ²	<input type="checkbox"/> ³	<input type="checkbox"/> ⁴																	
Very good	Quite good	Quite poor	Very poor																							
<input type="checkbox"/> ¹	<input type="checkbox"/> ²	<input type="checkbox"/> ³	<input type="checkbox"/> ⁴																							
<p>11. To what extent do the following factors influence the route that you take to your place of work.</p>	<p style="text-align: center;"><i>Please tick one box on each line</i></p> <table style="width: 100%; border: none;"> <tr> <td></td> <td style="text-align: center;">A great extent</td> <td style="text-align: center;">Moderate</td> <td style="text-align: center;">Very little</td> <td style="text-align: center;">Not at all</td> </tr> <tr> <td>a) Exposure to traffic</td> <td style="text-align: center;"><input type="checkbox"/> ¹</td> <td style="text-align: center;"><input type="checkbox"/> ²</td> <td style="text-align: center;"><input type="checkbox"/> ³</td> <td style="text-align: center;"><input type="checkbox"/> ⁴</td> </tr> <tr> <td>b) Gradient</td> <td style="text-align: center;"><input type="checkbox"/> ¹</td> <td style="text-align: center;"><input type="checkbox"/> ²</td> <td style="text-align: center;"><input type="checkbox"/> ³</td> <td style="text-align: center;"><input type="checkbox"/> ⁴</td> </tr> <tr> <td>c) Cycle lane provision</td> <td style="text-align: center;"><input type="checkbox"/> ¹</td> <td style="text-align: center;"><input type="checkbox"/> ²</td> <td style="text-align: center;"><input type="checkbox"/> ³</td> <td style="text-align: center;"><input type="checkbox"/> ⁴</td> </tr> <tr> <td>d) Other please specify</td> <td colspan="4" style="text-align: center;"><input style="width: 100%; height: 20px;" type="text"/></td> </tr> </table>		A great extent	Moderate	Very little	Not at all	a) Exposure to traffic	<input type="checkbox"/> ¹	<input type="checkbox"/> ²	<input type="checkbox"/> ³	<input type="checkbox"/> ⁴	b) Gradient	<input type="checkbox"/> ¹	<input type="checkbox"/> ²	<input type="checkbox"/> ³	<input type="checkbox"/> ⁴	c) Cycle lane provision	<input type="checkbox"/> ¹	<input type="checkbox"/> ²	<input type="checkbox"/> ³	<input type="checkbox"/> ⁴	d) Other please specify	<input style="width: 100%; height: 20px;" type="text"/>			
	A great extent	Moderate	Very little	Not at all																						
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c) Cycle lane provision	<input type="checkbox"/> ¹	<input type="checkbox"/> ²	<input type="checkbox"/> ³	<input type="checkbox"/> ⁴																						
d) Other please specify	<input style="width: 100%; height: 20px;" type="text"/>																									

12. Do you take the shortest route possible to your place of work when you cycle?

Yes

Please tick one box only 1

No

 2

13. How dangerous are these other modes of transport, to yourself, when you cycle to work?

Please tick one box on each line

a) Public transport

Much risk

Moderate

Very little

Not at all

 1 2 3 4

b) Cars/vans

 1 2 3 4

c) Motorcycles

 1 2 3 4

d) Other cyclists

 1 2 3 4

e) Pedestrians

 1 2 3 4

14. To what extent do the following factors deter you from cycling on any given day.

Please tick one box on each line

a) Weather conditions

A great extent

Moderate

Very little

Not at all

 1 2 3 4b) Need to carry bag/
equipment 1 2 3 4c) Dark mornings/
evenings 1 2 3 4

d) Multipurpose trip

 1 2 3 4e) Business travel
during the day 1 2 3 4

f) Other specify

15. Please indicate the importance of the following in your decision to cycle to work rather than use another form of transport.

Please tick one box on each line

a) Shorter route

Very important

Quite important

Not very important

Not at all important

 1 2 3 4

b) Cost Saving

 1 2 3 4

c) Time saving

 1 2 3 4

d) Health/fitness

 1 2 3 4

e) Varied route

 1 2 3 4

f) Contact with nature

 1 2 3 4g) Environmental
benefit 1 2 3 4h) Sense of
independence 1 2 3 4

i) Relaxing experience

 1 2 3 4j) Encouraging
employer 1 2 3 4

k) No alternative

 1 2 3 4

l) Other specify

17. Which of the following would encourage you to cycle to work more often?

Please tick **one** box on each line

	Great extent	Moderate extent	Very little	Not at all
a) Decrease in road congestion	<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4
b) More expensive parking	<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4
c) More expensive fuel	<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4
d) Road pricing	<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4
e) Better facilities for cyclist at work	<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4
f) Safer routes on/off road (eg lighting)	<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4
g) Other please specify	<input type="text"/>			

18. To what extent does each of the following deter you from cycling more often?

Please tick **one** box on each line

	Great extent	Moderate extent	Very little	Not at all
a) Journey length	<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4
b) Hills	<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4
c) Poor physical fitness	<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4
d) Lack of dedicated cycle lanes	<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4
e) Personal safety	<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4
f) Inflexible working hours	<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4
g) Need to carry baggage / equipment	<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4
h) Need to dress formally/appearance	<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4
i) Need to combine journeys	<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4
j) Weather	<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4
k) Danger from traffic	<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4
l) Lack of support from employer	<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4
m) Other please specify	<input type="text"/>			

19. Does your employer provide:

Please tick **one** box on each line

	Yes	No
a) Covered parking	<input type="checkbox"/> 1	<input type="checkbox"/> 1
b) Secure parking	<input type="checkbox"/> 2	<input type="checkbox"/> 2
c) Other basic cycle parking facilities	<input type="checkbox"/> 3	<input type="checkbox"/> 3
d) A financial incentive to cycle	<input type="checkbox"/> 4	<input type="checkbox"/> 4
e) A bike loan	<input type="checkbox"/> 5	<input type="checkbox"/> 5

20. How much risk do you think you face from the following when you cycle to work?

Please tick the box on the scale which comes closest to your opinion, where (1) means you think there is much risk, and 4 means you think there is little risk.

*Please tick **one** box on each line*

	Much risk		Little risk
a) Motor traffic	<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3 <input type="checkbox"/> 4
b) Illness due to pollution	<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3 <input type="checkbox"/> 4
c) Threat of personal attack	<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3 <input type="checkbox"/> 4
d) Poor condition of road surface	<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3 <input type="checkbox"/> 4
e) Poor condition of cycle route	<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3 <input type="checkbox"/> 4
f) Conflict with pedestrians	<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3 <input type="checkbox"/> 4
g) Poor night time lighting on roads	<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3 <input type="checkbox"/> 4
h) Poor night time lighting on off road cycle routes	<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3 <input type="checkbox"/> 4
i) Difficult junctions	<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3 <input type="checkbox"/> 4
j) Parked cars	<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3 <input type="checkbox"/> 4
k) Bike theft	<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3 <input type="checkbox"/> 4
l) Other cyclists	<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3 <input type="checkbox"/> 4
m) Other please specify			

21. Are you....?

*Please tick **one** box only*

Male	<input type="checkbox"/> 1
Female	<input type="checkbox"/> 2

22. What age group do you belong to?

*Please tick **one** box only*

a) Under 25	<input type="checkbox"/> 1
b) 25 –34	<input type="checkbox"/> 2
c) 35 – 44	<input type="checkbox"/> 3
d) 45 – 54	<input type="checkbox"/> 4
e) 55 or over	<input type="checkbox"/> 5

23. What is your occupation/job title?

Please put your answer in the box

Job title/occupation	
----------------------	--

24. If you have any further comments that you would like to make please add them here:

That's it! Thank you.

Would you please check that you have answered all of the questions. Please remember that all your replies are strictly confidential to the research team.

If you have any questions about the survey or need any help please contact Joanne Patterson at Cardiff University on telephone 029 20875977 or e-mail *Patterson@cardiff.ac.uk*.

Please remember that when returning your questionnaire that the freepost envelope does not need a stamp. If you do not have an envelope you can return the questionnaire to the freepost address on the front of this questionnaire without using a stamp.

In future we may want to talk to some of the people who have filled in the questionnaire. If you would not mind being approached again as part of this study could you fill your address and e-mail address if you have one in the space below.

Name	
Address	
E-mail	
Employer	

Thank you very much for taking the time to answer the questions in this survey.

Your name will be entered into the draw to win a 'Selle Royal' special edition Luxury gel saddle as our thanks to you for completing the form.

16. Please draw onto the map your usual route from home to work as accurately as possible. Please circle any junctions that you feel are dangerous. If your route goes off the map, please trace the extent of your route that is included on the map. Please use a coloured pen if possible.

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Appendix 4

Organisations involved in implementation of questionnaire

Appendix 4 - Organisations involved in the questionnaire survey for three cycling cities

Employer
AA
ACCAC
ACTION MEDICAL LIMITED
ADEL ROOTSTEIN LTD
ADMIRAL
ARRIVA TRAINS NORTHERN
ARUP
B NORTH PCT
BBC
BBC WALES
BCWA
BENEFITS AGENCY
Black Horse LTD
BOOTHAM PARK HOSPITAL
BOOTHAM SCHOOL
BRISTOL CITY COUNCIL
BRISTOL UNIVERSITY
BRISTOL ZOO GARDENS
BRITISH SUGAR
BRO TAF HEALTH AUTHORITY
BT
BURGES SALMON
C B HILLIER PARKER
CARD PROTECTION PLAN
CARDIFF AND VALE NHS TRUST
CARDIFF BUS
Cardiff Citizens Advice Bureau
CARDIFF COUNTY COUNCIL
CARDIFF L E A
CARDIFF LOCAL HEALTH GROUP
CARDIFF UNIVERSITY
Celtic Technologies Ltd
CITY OF BRISTOL COLLEGE
CITY OF YORK COUNCIL
CIVIL SERVANT
COLLEGE
COMPANIES HOUSE
CONTACT 24
CORPS OF COMMISSIONAIRES
COUTTS GROUP
CYCLE WEST
D AND C
DALKIA
DAS LEGAL EXPENSES INSURANCE CO LTD
DEAN & CHAPTER OF YORK
DEFRA
DEFRA
Department of Work and Pension
DEPT FOR WORK AND PENSIONS

DIFFERENT PLACES
DTLR
ECGD
Elephant.co.uk
ENERGY PARTNERSHIP
ENVIRONMENT AGENCY
FABER MAUMSELL
FAMILY FUND TRUST
FAMILY MATTERS LTD
Finance Wales plc
Fulmar TV and Film
Gerling NCM
GNN
GOVERNMENT OFFICE SOUTH WEST
Halcrow group ltd
HIGH WAYS AGENCY
IBM
IKEA
INLAND REVENUE
INLAND REVENUE
INNOGISTIC SOFTWARE PLC
INTERNATIONAL BACCALAUREATE ORGANIZATION
JOHNSON CONTROLS LTD
JOSEPH ROWNTREE FOUNDATION
KELLYS AGENCY
KPMG
KRAFT FOODS
LLOYDS TSB
LLOYDS TSB
M BRITAIN YORK LTD
MAJOR SECURITY SERVICES
MARKS AND SPENCER
MARLWOOD SCHOOL
MBA PASTURES YOUTH CENTRE
MEAT HYGIENE SERVICE
MEDIA EDUCATION WALES
MERGE DATA LIMITED
Metal Fabrications
MINISTRY OF DEFENCE
MOTABILITY FINANCE LIMITED
NAT WEST
NATIONAL ASSEMBLY
NATIONAL MUSEUM WALES
NESTLE
NEVISPORT
NHS
NORTH BRISTOL NHS TRUST
NORTH YORKSHIRE EMERGENCY DOCTORS
NORWICH UNION
OCS
OFSTED EARLY YEARS
OPEN UNIVERSITY

OSBORNE CLARKE
PARK HOUSE FINANCE DEPARTMENT
PARSONS BRINCKERHOFF
PAUL GOODING
PERTEMPS
PINDAR BRISTOL LTD
PORTAKABIN LIMITED
ROYAL BANK OF SCOTLAND
SELBY & YORK PCT
SIFT
SOCIAL SECURITY OFFICE
SOIL ASSOCIATION
SOUNDWELL CENTRE COB COLLEGE
SOUTH GLOUCESTERSHIRE LEA
South Riverside CDC
SOUTH WEST REGIONAL DEVELOPMENT AGENCY
SSI IMPREGELIO
ST LEONARDS HOSPICE
STERILE SERVICES INTERNATIONAL
Sustrans Cymru
TAFF HOUSING ASSOCIATION
TERRY SUCHARD
TESCO
THE APPEALS SERVICE
THE MOUNT SCHOOL
THE RECYCLING CONSORTIUM THE CREATE CENTRE
THE WORD DIRECT
TRINITY ROAD LIBRARY
UHE
UHW
UNDEB Y MYHYRWYR
UNIVERSITY OF YORK
UWCM
UWE
UWIC
VENTURE PORTRAITS
WCI LTD
WDA
WELLWOMEN INFORMATION
WWF-UK
YORK CITY ART GALLERY
YORK COLLEGE
YORK CVS
YORK DISTRICT HOSPITAL
YORK HEALTH TRUST
YORK HOUSING ASSOCIATION
YORKBOAT
YORKON LTD