Traffic modelling in cities – validation of space syntax at an urban scale

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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. The research described in this paper uses spatial analysis modelling procedures based on space syntax to investigate the potential to model aggregate traffic flows at an urban scale. The research has demonstrated that space syntax modelling is an effective means of representing an urban scale motor traffic network, however, modifications to the original model were required to achieve a correlation between modelled and measured motor traffic flow comparable to other modelling procedures. Weighting methods were tested with 'boundary weighting' found to be effective at representing traffic crossing the boundary of an isolated urban sub-area, but 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. The modelling approach has the potential to be extremely useful at an early planning stage to represent changes to flows across the network and to be useful for different modes.

Introduction

In 2007 the EU committed to move Europe to a low carbon economy and it was agreed that carbon dioxide (CO_2) emissions would be cut by at least 20% of 1990 levels by 2020 [1]. The UK Climate Change Act 2008 [2] set a target of 80% reductions on 1990 baseline UK CO_2 emissions levels by 2050. These types of legislative intervention will need to be accompanied by significant changes in behaviour across all aspects of the built environment at all scales.

Passenger cars in the UK emitted 63% of all greenhouse emissions from road transport in 2009 [3] and 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 1.

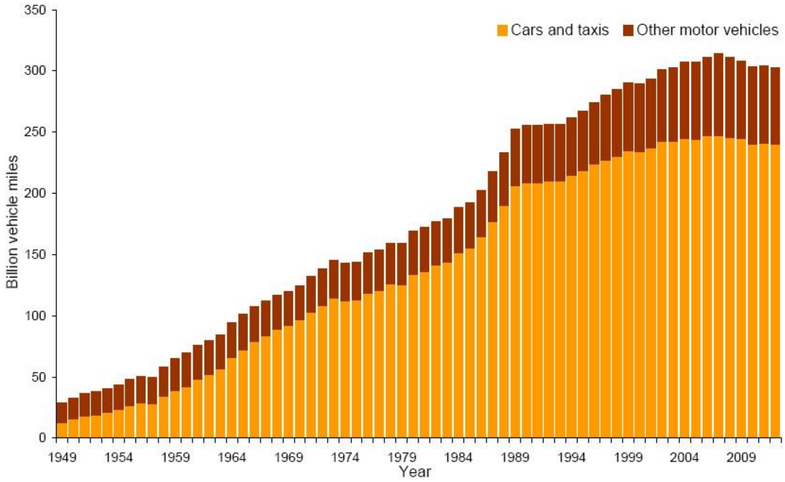


Figure 1 - Increase in road traffic in Great Britain [4]

To reduce CO_2 emissions in a city or region, roads need to become more accessible for sustainable modes of transport and 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. A strategic vision is required which considers the needs of each user of the network and by using an urban scale approach and infrastructure change can be combined with spatial, economic, legal, psychological and educational policy measures [5]. 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. 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.

Models currently in use for such purposes include the traditional ‘Four Stage Model’ [6] and the SATURN model [7,8]. The ‘Four Stage model’ was designed for large scale road construction projects and requires extensive data collection and model estimation and forecasting exercises which may take years to collate [9-11] .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 economically viable [12].

The SATURN (Simulation and Assignment of Traffic to Urban Road Networks) traffic model, which is applicable at the fourth stage of a four stage model, enables analysis of traffic management schemes on localised networks [7,8] and presents a relatively detailed representation of the urban road network requiring a modest level of data. However, data required is very detailed and clear visual outputs are limited which prevents this tool being used for quick and simple assessments. Multiple centrality assessment (MCA) was introduced in response to the concept of space syntax [12]. MCA allows for a metric calculation of distance, whereas space syntax calculations are relative. MCA reduces subjectivity however, the creation of maps requires the use of very large information resources. An appropriate, validated traffic model for scoping at initial planning scale that can be used at an urban scale and can be combined with other modal data is therefore required.

Space syntax modelling techniques [14] are based on a configurational axial map of a space, which indicate how spaces are located in relation to each other [15]. Integration values are assigned to each ‘space’ in a network to represent attractiveness [16] and integration values can be used to ‘identify routes that are potentially more likely to be travelled’[17]. As links are not aggregated into zones, all trips are illustrated on the axial map. Traditional space syntax has used to analyse the effect of the configuration of space on a broad range of architectural and planning applications [17-20]. Investigations undertaken to confirm the predictability of integration values have taken place for different scales of spaces and for different modes of transport [17, 21, 22].

Various characteristics of the network infrastructure may influence integration values and can address limitations within the space syntax approach [28]. ‘Weighting factors’ allow the incorporation of a degree of real world complexity into what would otherwise be a relatively non-complex modelling approach. Weighting factors needs to be replicable and consistent to give validity without committing the end user to a greatly increased burden of data capture or complex data manipulation. Weighting factors previously implemented include:

- **‘edge effect’** relates movement patterns within a catchment area to the larger catchment area [16, 21-24] . Traditionally, an area is dealt with in isolation within space syntax considering the lines within the axial map only. Extending an axial map to contain a larger ‘catchment’ area is not that time consuming on a small scale, but when considering urban areas of over 100 km^2, the additional time resource to represent the ‘edge’ of a map would be large, a limitation of space syntax.
- **‘Radius integration’** can be used to appraise local integration of axial maps, these have been shown to improve levels of correlation between predicted and real flow for non-motorised transport at a small scale [24-28].
- Street features that influence urban transportation such as road width, pavement quality and traffic lights are not widely considered in configuration analysis [17]. ‘**Road weighting**’

can be used to allow specific road characteristics that influence the potential attractiveness of a road to be represented. 'Place Syntax' has been developed for pedestrian to 'load' geographical data onto predicted pedestrian movements within space syntax [29] .

'Weighting' tests have been implemented using classification methods applicable to a small area of a city such as a neighbourhood [24, 28, 29], however, at city or regional scale data requirements are too time consuming to collect. Consistent methods of classification within and across cities are required that can be replicated both in the future and in other cities and regions in the UK and internationally.

Despite a number of attempts, strong evidence to correlate urban scale data and traffic flow using weighting methods is still lacking and that improvements to mapping are required to improve correlations further.

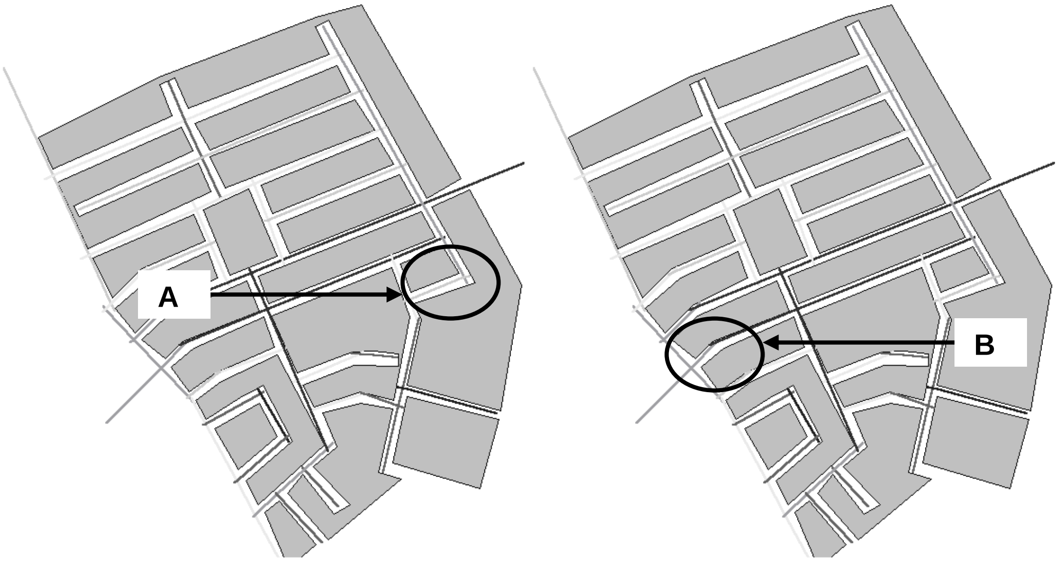
Method

This paper describes the validation of space syntax to quantify relative levels of traffic flow for an entire road system for a city or region. The integration of the road network at any given point is investigated, together with analysis of the potential to include both local and strategic roads by defining weighting methods to improve modelled traffic flow predictions and test weighted methodology for the traffic flow model on case study cities. Validation of the traffic model was undertaken in Cardiff with further tests taking place in Leicester, Leeds and Neath Port Talbot as established relationships with local authorities in these cities existed which enabled the provision of relevant data to develop the modelling work. The research focused on urban areas as there is increased potential for modal shift and although the research was undertaken in UK cities, the findings and the methodologies developed are applicable to other international urban areas. The traffic flow modelling work has been developed at the Welsh School of Architecture, Cardiff University as part of the Energy and Environmental Prediction (EEP) model [30].

The spatial analysis model is based on the commonly used Geographical Information System (GIS) desktop software, MapInfo version 12.0, published by MapInfo Corporation as:

- 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, 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.

A road/path is represented as a line or series of lines that follow the line of sight along a network - ‘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 as illustrated in Figure 2.



A - change in direction due a non-linear route.
B - route is not accessible for cars and so no link is made between two juxtaposed roads.

Figure 2 - An axial map demonstrating axial lines for traffic

The software simulates journeys from all potential origins (axial line) to all potential destinations (all other axial lines) and 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 [21, 26]. 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. A full description of model creation including algorithms have been described [31]. 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.

Basic axial map techniques are presented in this paper as they are simple and therefore relatively quick to apply at an urban scale. The simpler the modelling and 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 competence. A staged approach was used during the validation process to potentially limit the data collection required. Each stage has been analysed individually to investigate its effectiveness in terms of modelling accuracy.

Motor traffic data was collected from local authorities for a wide range of roads and all motor traffic flow data was converted to average hourly two directional motor traffic flow. The relationship between measured traffic flow (independent variable) and model calculated integration values (dependent variable) describe how well the model was able to predict real traffic flow figures. The aim was to achieve strong positively correlated variables – as traffic flow increases, integration values increase.

Two levels of ‘depth’ were incorporated into the model for boundary weighting assessments to represent a greater variation of incoming traffic at the boundary, illustrated in Figure 3.

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 3. 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.

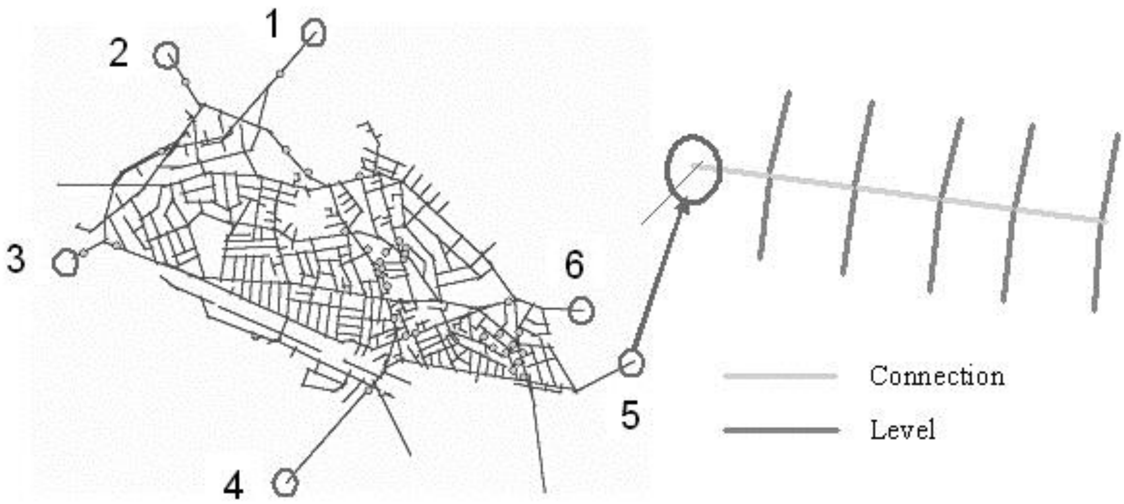


Figure 3 - Example of the boundary weighting for urban case study area

The model has been modified to include features such as road type, road width and road furniture, such as zebra crossings and speed bumps into integration value calculated. Discussions with local authority staff and some preliminary investigations using GIS maps and site visits revealed that the level of data collection required would break the criterion that data for the final model should be relatively easy to collect, it was decided that a road classification systems would be implemented for road weightings for replicability and simplicity. Roads were classified for analysis:

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 used by the Transport Planning Department of Cardiff County Council based on how roads are ‘used’ and was informed by local knowledge.

The classification system most suitable was motorways (M), A roads, B roads and minor roads as these are used nationally and can be easily identified from a good road map. The classification was extended to allow for distinction between speed limits as speed of traffic was considered likely to have a significant impact on the amount of non-motor vehicles, air pollution and accident rates. Roads across the city were allocated to either:

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

The road weighting methodology was tested on the whole of Cardiff as very few motorways or principal routes were within the smaller case study area. Data from 148 points was available from key routes, strategic counts, screenline sites and from within the central area of the city.

A staged approach was used during the validation process to potentially limit the data collection required. Each stage has been presented and analysed individually to investigate effectiveness in terms of modelling accuracy.

RESULTS

Stage 1 – Validation of Traffic Flow Model with Basic Flow Data - **Cardiff County Council (CCC) provided data for 58 coil detectors located at permanent positions on most major routes throughout Cardiff for a period of eight weeks during the autumn. Global integration values from the axial map within the spatial analysis model were obtained where count data was available. A Global integration value is calculated when no modifications are made to basic integration procedures within the spatial analysis model. Coil detector and global integration values were analysed and an R^2 value of 0.07 was obtained. Spearman rank correlation co-efficient which was significant at 0.05 level, gave a correlation coefficient of 0.246. Both indicated a weak, positive correlation which was expected as (i) the data set was limited, (ii) traffic entering the city boundary was not accounted for, and (iii) road features that might affect 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 traffic flow. Figure 4 illustrates that more integrated roads are located towards the centre of the map (darker lines) with less integrated routes around the periphery (lighter coloured lines).

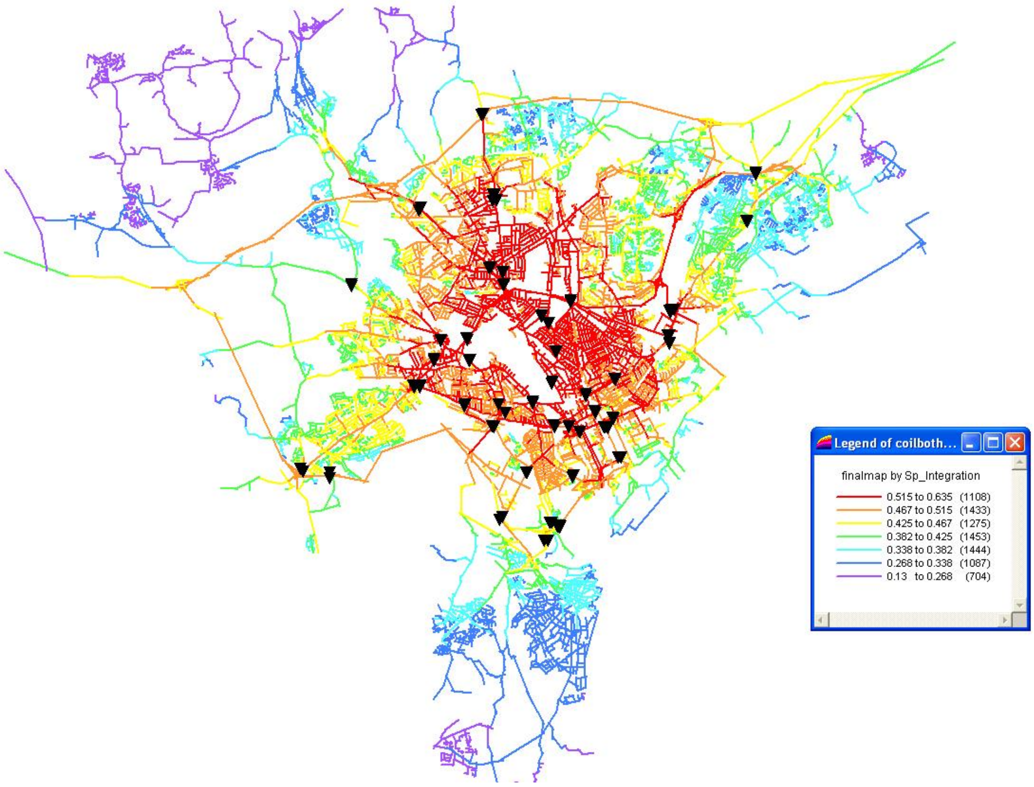


Figure 4 - Global integration map for Cardiff motor traffic flow

Stage 2 – Incorporating an Increased Range of Traffic Flow Data – Manual counts and temporary Automatic Traffic Count surveys or 'tubes' were carried out/positioned on roads with a range of flows in a small urban case study area of Cardiff as illustrated in Figure 5.

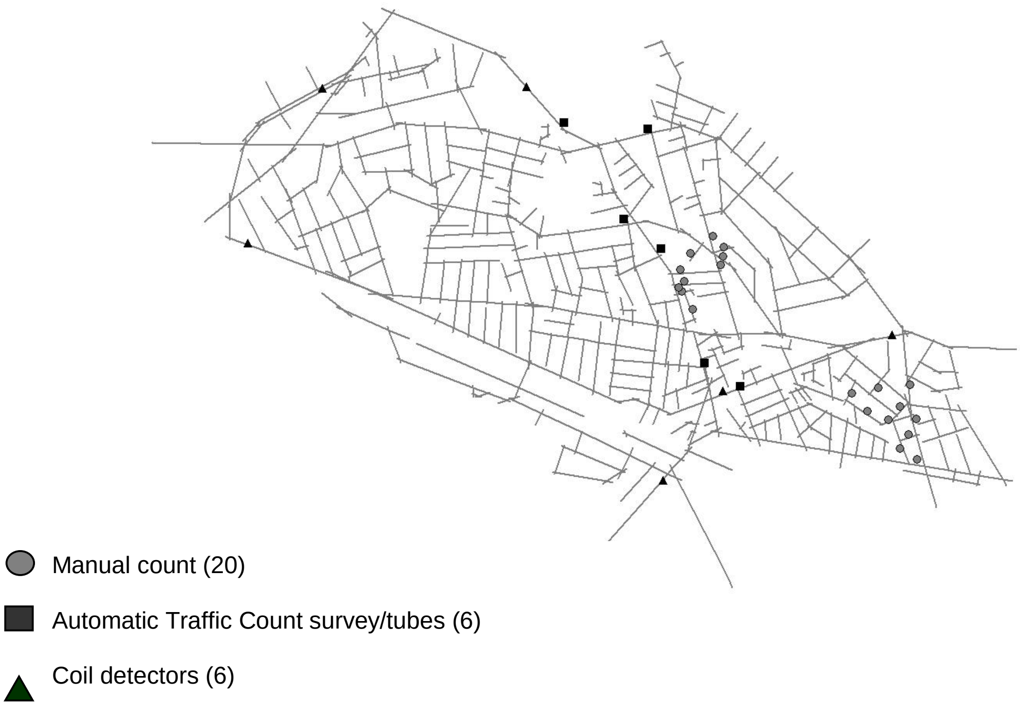


Figure 5 - Axial map of urban case study area illustrating count locations

Two analyses were considered for the urban case study area:

- Global integration values obtained for the whole axial map of Cardiff which investigated the impact of looking at a sub-area of a larger space;

- Global integration values were calculated assuming the urban case study area was an isolated space, excluding the axial lines for the rest of Cardiff.

When considering traffic flow figures correlated with the global integration values calculated from the axial map of the *whole of Cardiff* an R^2 value of 0.68, a reasonably strong relationship supported a correlation co-efficient of 0.8, which also suggests a strong, positive correlation.

For locations with flows of more than 100 vehicles per hour with an R^2 value of 0.65 and correlation co-efficient of 0.85, were calculated suggesting a strong, positive correlation. On roads with less than 100 vehicles per hour (sample size 12, below the suggested figure of 20 for a regression analysis test) an R^2 of 0.016 signified a poor relationship. This indicates that the model may be able to predict traffic on roads of frequent higher flows but not for roads which have infrequent flow.

When dealt with in isolation, results for the urban case study area indicate an R^2 of 0.05 and correlation co-efficient 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.

Stage 3 - Extending the Sample Across the City - Data from 117 locations from across Cardiff on roads with a range of vehicle flows from 6 vehicles per hour to 4,091 vehicles per hour was available. The relationship between motor traffic flow and global integration was found to be not very strong when all 117 count locations were included, resulting in an R^2 value of 0.3. A correlation co-efficient of 0.632 was obtained which represents a moderate, positive correlation. Weak correlations are also obtained when 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).

Application of Radius Integration - Radius integration [25] was undertaken to identify whether limiting spatial analysis to a local integration produced a more accurate correlation with motor traffic flow values. Radius analysis was undertaken for the urban case study area and city wide scales. Radial depth values of 3 and 7 were applied at both scales [25]. Example of maps for radial integration are illustrated in Figure 6 (Cardiff radius 3) and Figure 7 (Cardiff radius 7).

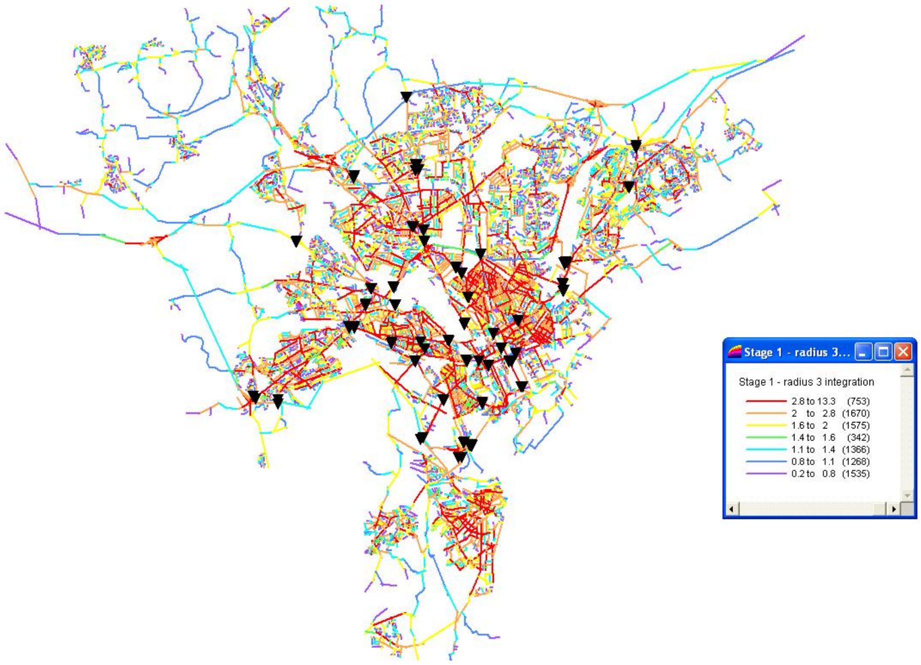


Figure 6 - Radial 3 integration map for Cardiff

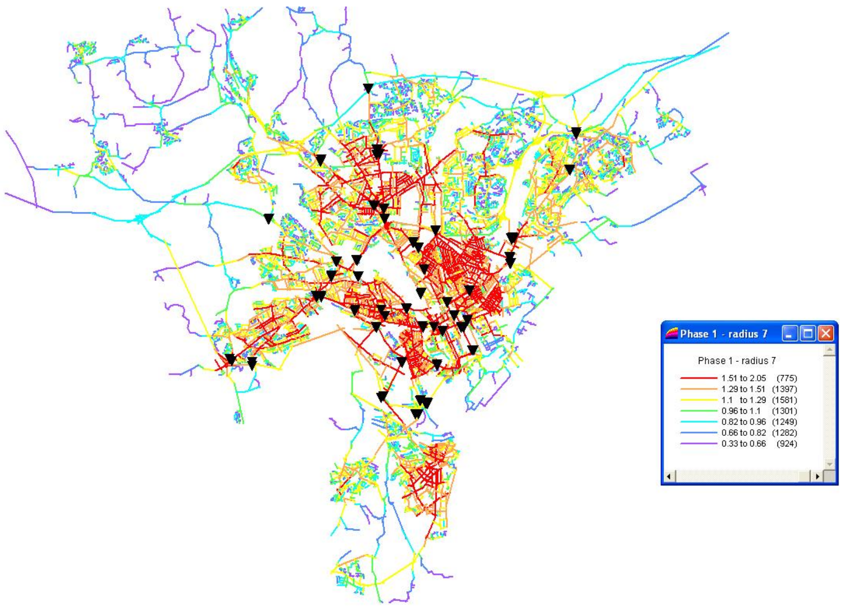


Figure 7 - Radial 7 integration map for Cardiff

A summary of the results of the radial integration tests for each stage is provided in Table 1. R^2 results indicate a poor relationship between motor traffic data and radial integration values. Stronger correlations were calculated using global integration than either of the radial integration calculations both city wide and urban case study area were considered, and when the extended city wide data set was used which was supported by correlation co-efficient results.

Table 1 - Table illustrating differences between global and radius integration results

Stage	Test	Integration Method	R^2 value	Correlation co-efficient
1	City wide coil detectors	Global integration	0.295	0.246
		Radius 3	0.00	-0.059
		Radius 7	0.00	-0.018
2i	Urban case study	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

As the results of the radial integration calculations are all weaker than global integration calculations, it was confirmed that this was not an appropriate method to be used further at an urban scale.

Application of boundary weighting - Boundary weightings were allocated to roads classified as motorways, built up (BU) and non-built up (NBU) roads only, as real traffic flow data was available for limited locations at the boundary of a city. Boundary weightings were tested on the urban case study area and where strong results were obtained methods were applied to the whole of Cardiff and other cities in order to establish whether the method was valid at a larger scale and in other locations. Ideally the methodology for boundary weighting should be applicable and replicable to any area and should not rely on real traffic data which may not be available.

Boundary Weighting Tests on Case Study Urban Area – The case study urban area 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 with 35 data points. Fifteen boundary weighting methods were tested as illustrated in Table 3. Tests 1 – 6 used real 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 data not associated to the map. 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 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 traffic to be used to provide a weighting, similar to the 'Edge effect' method[16, 21-24]. The values used in the fifteen tests are presented in Table 2.

Table 2 - Weightings applied within each test case for case study urban area

	Western Avenue		High Street		Cowbridge Road East		Leckwith Road		Wood Street		Lower Cathedral Road	
Test	**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

Linear regression analysis was carried out on all data and results are illustrated in Table 3. Four tests recorded no result indicating no relationship (tests 3, 7 and 8), where results were obtained, these varied from an R^2 of 0.10 to 0.77. The strongest relationship between real 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 R^2 value of greater than 0.7.

Table 3 - Table of tests and results from 15 boundary weighting tests undertaken on urban case study area

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

Test	Connections	Levels	R^2 value	Order of results	Pearson's Correlation Co-efficient	Order of results
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*	Radial distance from axial line (1% of number axial lines in whole map)	None entered	0.46	6	0.68	5
12*	Radial 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

The results for tests 11, 12 and 15 which relate the boundary location to the space directly around it demonstrated that a relationship did exist between average hourly traffic flow and boundary weighted predicted integration values. 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 3, 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.

Boundary weighting tests on the whole of Cardiff - The road network of Cardiff was represented by 7,731 axial lines. The count locations at the edge of the City were identified as M, A or B roads and these were also further classified as NBU (>30mph) and BU (30mph or less). The tests undertaken, using the same principles as for case study urban area, are presented in Table 4. 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 4.

Table 4 – Summary of tests and 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 weighting				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 coil 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	M roads – 5000 A roads – 2000	M roads – 5 A roads – 2	0.32	3	0.582	7

	B roads – 2	B roads – 1000	B roads – 1				
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	M roads – 0.1% of axial lines whole city	0.17	9	0.408	9

		NBU – 0.5% of axial lines within whole city BU – 0.25% of axial lines within whole city	NBU – 0.05% of axial lines within whole city BU – 0.025% of axial lines within whole city				

Table 4 illustrates 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 an 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.

Weighting key routes within the road network using the road weighting facility may improve correlations.

Application of road weighting – Road weighting tests were undertaken using global integration values with no weighting as well as a selection of potentially replicable boundary weighted results in order to determine the individual effectiveness of the weighting technique, and the overall aggregated improvement when combined with boundary weighting. Three road weighting tests were applied to four different sets of integration values are described in Table 5, these include:

1) Global integration values with no boundary weighting;
2) Global integration values calculated from boundary weighting using County and Core roads;
3) Global integration values calculated from boundary weighting based on M, A and B road weightings;

Global integration values calculated from boundary weightings based on M, BU and NBU road weightings.

Table 5 - Classification of road types and different road weightings implemented

Road type	Road weighting test		
	1	2	3
Motorway	4	5	3
NBU Principal route >30mph	3	3	2
BU 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 6. 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. Pearson's correlation co-efficient 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).

Table 6 - 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	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	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 weightings	0.17	0.53	0.66	0.82	0.70	0.83	0.70	0.83

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. 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.

Application to Other Cities/Region - The final stage of the validation process was to test the most successful weighting methods on three other UK cities/regions. Traffic flow figures were obtained for Leicester and Neath Port Talbot County Borough Council (NPTCBC). For Leeds, predicted traffic flow figures from SATURN [7, 8, 16] were correlated with those from the spatial analysis map for the city provided by researchers from the University of Leeds [32]. 40 locations were selected throughout Leeds to cover a wide range of road types and flows. Table 7 Table compares the four cities/regions. Leeds has a much denser road network than NPTCBC. Much less traffic flow data was available for the additional cities and regions than the original study city of Cardiff.

Table 7 - 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
NPTCBC	9,207	23

Global integration was run for each of the three cities/regions. Three tests were then carried out to compare traffic flow figures with integration values based on the most replicable methods and data available:

- Global integration with no weighting;
- Global integration values with road weightings associated with motorway/NBU/BU;
- Boundary weighted global integration values with M/A/B roads weighted together with road weightings for motorway/NBU/BU routes;

- Global integration values calculated using boundary weightings using % axial lines and road weightings on M, BU and NBU.

M, A and B routes were classified using the motorway, NBU and BU system to allocate road weightings as this demonstrated the greatest improvement from no road weightings in the test for Cardiff (test D, table 6). The results for the additional city/regions can be seen in Table 8 which illustrates that all tests significantly improve both the R^2 and correlation co-efficient when compared to the global integration value with no weighting.

Table 8 - Results from road and boundary weighting tests in different city/regions

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	Correlation co-efficient	R^2	Correlation co-efficient	R^2	Correlation co-efficient	R^2	Correlation 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
NPTCBC	0.22	0.53	0.82	0.70	0.86	0.78	0.82	0.70

Results for Cardiff, Leeds and NPTCBC indicate little improvement between results generated using road weighting only (test B), and those generated using a combination of road weighting and boundary weighting (tests C and D). For Leicester tests B and D provide similar 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 traffic flow data obtained from motorways for Leicester.

Discussion

A validation process has been undertaken and presented through stages to identify the minimum level of data needed to implement the urban scale traffic flow model effectively.

Calculations for stage 1 conveyed a positive correlation, as expected the area was dealt with insolation with a limited set of data and a narrow range of road types being present. An urban case study area was used to demonstrate that by using a wider range of flow values a much improved correlation between average hourly 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 area and the surrounding space. When the case study space was dealt with in isolation the relationship remained weak. This reinforces the need to enable the model to consider traffic which crosses the boundary from the surrounding area.

When the city is considered as a large, isolated space, correlations are poor. When considering the entire city a small increase in correlation was found when data from more 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 prediction capabilities of the spatial analysis model were required, as opposed to the inclusion of additional monitoring data.

Accounting for traffic movement across the model boundary did result in a significant improvement in the correlation between traffic flow and global integration for the urban 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 traffic flow for a small isolated area of a city, for a wide range of roads.

Radial integration, allowing local movements to be reflected in the integration values, resulted in the correlation between average hourly traffic flow and radial integration calculations being weaker than the global integration calculations used in the standard space syntax model. Radial 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 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 traffic flow were only marginally improved at an urban 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 traffic flows on routes that are designed to carry higher 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 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.

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. Weighting factors presented within this paper are only capable of accounting for road characteristics that are fairly consistent through time and across space. In reality factors that could potentially affect 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. 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 results from this research demonstrate that data obtained from the spatial integration map are similar to results generated by the SATURN model for the city of Leeds, but require much less origin/destination based data, and therefore less expense, to make the calculations and can therefore be considered a suitable alternative particularly at the initial planning stage.

The model was limited in its ability to predict 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 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 traffic flows. Further research into methods to more accurately accommodate these low flows into the model should be undertaken.

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 [16]. As indicated, [16] and from 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.

Conclusion

A process of validation for a traffic flow spatial analysis model has been presented. 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.

The application of road weightings to global integration values without incorporating boundary weightings would be the recommended method to predict 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. By applying the tests to three other UK cities/regions it has been demonstrated that the space analysis modelling methodology and the weighting methods developed are transferable to other urban areas and can be implemented using readily available levels of traffic data.

The results described above demonstrate the use of spatial syntax as a means of representing an extensive urban transport network. The model, which is based within a widely available GIS platform, has been shown to produce an output that correlates well with measured 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.
The creation and utilisation of a space analysis axial map represents 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.

The model could be used to help to identify routes which are used most by motor traffic, and assess the impact of modifications to road infrastructure at an urban scale to encourage the uptake of non-motorised transport to reduce emissions. 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 at a postcode level [30,33]. This research contributes to the further development of space syntax as an urban scale modelling tool for motor traffic.

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