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# EMERGENT ROUTE CHOICE BEHAVIOUR, MOTORWAY AND TRUNK ROAD NETWORK: the Nantes conurbation

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## Abstract

Road network models have traditionally characterised network performance in terms of an average travel time associated with each link in the network, which varies according to the level of traffic using the link. However, this characterisation ignores the influence of network geometry on route choice behaviour. Previous Space Syntax research in inner city contexts has used topological distance minimisation together with road capacity or compared metric, topological and geometric distance showing a high degree of association with vehicular flow level using spatially dense counts dataset. It has been shown that road network geometry strongly influence the traffic flow pattern through quantifiable properties of the network geometry, where topological distance minimisation and effective road width account for the majority of the variance in flows from street to street ( $r^2 = 0.8$ ). Such studies have focused on high-density urban environments and street network. The originality of this paper is to examine this relationship in the context of sparsely built suburban areas and motorways, trunk roads and feeder roads. The case of Nantes conurbation is used. Population density, activity locations, shop and supermarket locations and commuters' journey length distribution are mapped and analysed qualitatively. The spatial model covers an extent of 570 km<sup>2</sup> - including a 12 km diameter orbital motorway, several surrounding communities, and more than 700,000 inhabitants. This paper compares generic path selection link assignment using three different distance minimisation approaches: metric, topologic and angular. Using an automated vehicular counts (156) dataset on motorways, trunk and main roads, accounting for more than 3.500,000 vehicles/day, it was found that the correlation between topological closeness compounded with road capacity and vehicular flow levels increased with every step upwards in radius, peaking at  $r^2 \sim 0.84$  at radius-n. The study uncovered for the first time the role of axial entropy in relation to the motorway network. The results of this study suggest that road network geometry analysis can be a powerful predictor in low-density environments with a relatively sparse count dataset. The paper concludes with a discussion on the use of such analysis to strategically assess vehicular network design in relation to road network performance and interface, journey length reduction and road network legibility.

## Introduction

Since the publication of Newman & Kenworthy et. al 1989 which linked urban density to non renewable energy consumption there has been a growing interest in incorporating urban form indicators such as

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density and intensity, land use distribution and mix, street connectivity and scale, aesthetic qualities and regional structures into transport planning and travel analysis as well as to relate urban design to transport performance. Reducing and better managing private motorised transport has become an important part of the international urban sustainability agenda. The increasing levels of traffic congestion have prompted road authorities around the world to place more emphasis on improving the efficiency and capacity of existing roads through Intelligent Transportation Systems (ITS) technologies. An important component of ITS are Advanced Driver Information Systems (ATIS) and Advanced Traffic Management Systems (ATMS). The two systems are often integrated because successful operation of both requires a sensor network that collects real time traffic data and on-line data analysis that identifies the current state and predicts the future state of the transport network. ATIS systems provide drivers with real-time information about traffic conditions, accident delays, roadwork, road charging and alternative route guidance from origin to destination. Some of the methods used for providing drivers with this information include traffic information broadcasting, pre-trip electronic route planning, on-board navigation systems and electronic route guidance systems. The principal aim of these systems is to influence drivers' behaviour on route and departure time decisions in order to improve mobility and reduce traffic congestion and emissions. ATMS takes advantages of the information by operating traffic control devices such as traffic lights, incident management, speed limits, etc.

Since 2003 the UK government has published five key strategic documents relevant to ITS. One of the major ITS policy themes is to provide better prior to travel and on route travel information helping to match supply and demand so that travellers can make informed choices on when and how to travel. Most previous studies examined the impact of ATIS on route choice and traffic equilibrium. This is not surprising because it is conceivable that the most significant impact of ATIS would be on departure time and on route choices during the journey. These studies differ in assumptions about user responses to information (route switching behaviour, fixed and variable origin-destination (OD) demand), traffic assignment criteria for informed and uninformed drivers, quality of the information, types of congestion, market penetration of equipped vehicles and properties of the traffic models (static, dynamic assignment, and queuing models etc.). With regard to driver behaviour though, most studies make unverified assumptions about driver behaviour (Zhang and Levinson, 2005). This paper will try to address this and investigate the spatial geometry of road network layout and how this may influence route choice.

### **Drivers' Route Choice, Literature Review**

The provision of driver information by ATIS can induce a number of possible short-term responses from the users. Drivers, knowing the level of congestion on chosen routes, may decide not to travel at all, change destination, change departure time, change transport mode or choose a different route.

The need to evaluate the impact and viability of ATIS and anticipate the resulting transport conditions under such a scheme on predicting transport conditions has highlighted some of the limitations of existing urban transportation models (UTM), the conceptualisation of route choice assignment and at the same time brought to the fore the possible importance of network knowledge and drivers' spatial ability in relation to route choice Ben-Akiva et al (1999), Ramming (2002), Hainan Li (2004).

The problem of route choice for a driver might be stated as follows: given the characteristics of the trip to be made (e.g. purpose, time,

origin, destination, and mode), together with the attributes of the alternative routes, and the driver's personal characteristics combine when the "best" route is selected Antonisse (1989).

Polydoropoulou et al. (1994) describe the decision-making process of route choice as a dynamic progression. A learning process is central to the driver's cognition as the information acquired through the experience of earlier travel choices is processed before the next decision is made. Moreover, the various characteristics of each known alternative route do not have the same importance in a driver's final decision. On the basis of relative importance of impact factors, drivers formulate a choice set of sufficiently attractive alternatives. From this set drivers make their choices, with the chosen route being the one that best satisfies their needs and are consistent with their personal constraints and preferences. Inertia also plays a role in travel choice behaviour, dictating that certain thresholds must be crossed before drivers change their habitual behaviour.

Empirical research on route choice behaviour shows that drivers use numerous criteria in formulating a route: travel time, number of intersections, traffic safety, traffic lights and other factors. Drivers' experiences, habits, cognitive limits (spatial ability and spatial knowledge) and other behavioural considerations may also produce variations in route choice.

- the physical environment, including the network infrastructure which determines, for example, travel possibilities and their characteristics
- the socio-demographic environment, including the household characteristics like modes of transport chosen, age, and the like.

Jan et al. (2000) grouped all the possible factors that influence drivers' route choice behaviour into four groups, as shown in Table 1.

**Table 1:**

*Route Choice Factors.*  
Source: Jan et al. (2000)

Driver	Age, gender, life cycle, income level, education, household structure, race, profession, length of residence, number of drivers in family, number of cars in family, etc.
Route	Travel time, travel cost, speed limits, waiting time
Road	Type of road, width, length, number of lanes, angularity, intersections, bridges, slopes, etc.
Traffic	Traffic density, congestion, number of turns, stop signs, and traffic lights, travel speed, probability of accident, reliability and variability in travel time, etc.
Environment	Aesthetics, land use along route, scenery, easy pick-up/drop-off, safety, parking, etc.
Trip	Trip purpose, time budget, time of the trip, mode use, number of drivers
Circumstances	Weather conditions, day/night, accident en route, route and traffic information, etc.

Researchers have also found that time-related variables are not the only ones to be considered in traffic assignment procedures. Driving effort, which was measured on a psychological scale, has also been found to be of considerable influence in the individual's route choice process (Stern et al. 1983). In their study, driving effort is measured by the number of turns along an alternative route. Their findings showed that the effect of the number of turns is much stronger on short journeys. It is known however, that these travellers are more likely to change the time of their departure than to take alternative routes. In early ATIS, it has also been found that suggested alternative routes based on shortest metric distance revealed considerable consumer dissatisfaction with the routes generated by algorithms similar to those used in traditional transportation planning models, e.g. shortest travel time (Schofer, Koppelman and Charlton (1997).

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Over the years UTM assignment components have adopted the shortest-path routing because of its simplicity (Duffell and Kalombaris 1988, Huchingson 1977, Wachs 1967), in real life, drivers' routes are likely to significantly deviate from the fastest path (Abdel-Aty et al., 1996). Directness Huchingson (1977) and congestion Wachs (1967) were among the most important reasons cited in relation to route choice.

Using a shortest metric path algorithm implicitly assumes unrealistically that the driver being modelled is aware of all the links (and their costs) that are used by the algorithm. Jan et al (2000) examined driver route choice data recorded by Global Positioning System (GPS) receivers, and present anecdotal evidence that the drivers in Lexington, Kentucky, did not select the shortest path. The authors state that the data does not allow further analysis of why the drivers did not choose the shortest path.

These discrepancies could partly account for excess commuting. This is the additional journey to work travel represented by the difference between the actual average commute and the smallest possible average commute, given the spatial configuration of workplace and residential sites, for a critical review see Mae and Banister (2006). When congested travel time is chosen as the objective variable, the problem becomes more complex, as congested travel time is a function of the volume of drivers using a link and will require dynamic traffic assignment capabilities.

Research on route choice aims to provide guidance on factors affecting drivers' decisions and to understand the strategies that drivers use to determine their route choice as well as route change heuristics. Some of the research findings show that

- drivers rely on their spatial knowledge about the built environment to make travel-related decisions which include job and residential location, vehicle ownership, activity schedule, activity location, travel mode and routes.
- the decision-making process is also typically subject to a number of determinants and constraints imposed by the natural, built, economic, and social environment, as well as the imperfection of travellers' perception and cognition capabilities Hensher and Goodwin (1978), Golledge and Stimson (1997).
- information plays a key role in travellers' perception, cognition, and decision-making processes.
- drivers learn about the environment through various information sources, including personal experience, inter-personal communication, maps, and mass media.

This research, however, has little to say on the systematic influence of urban design or transport network layout factors. In particular, no rigorous analysis of large scale transport network layout has been conducted to date. Although factors that influence drivers' mode choice are relatively clear, route choice remains an important but poorly understood problem. No systematic attempt has been made to characterise a-priori the effect of the built environment and large scale transport network layout on route choice.

The objective of this research is to investigate large scale transport network layout characteristics as factors influencing route choice using spatial analysis techniques to assess the relationship between street/road accessibility and drivers' route choice.

## Methodology

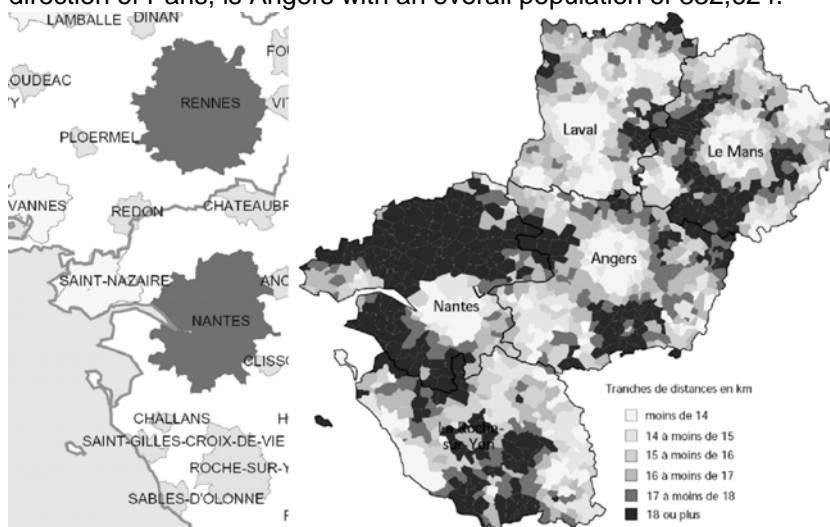
The role of spatial accessibility in pedestrian, cyclist and vehicular movement has been well documented (Hillier et al., 1993; Raford et al, 2005, Penn et al., 1998). Standard space syntax graph representation of the transport network relies upon the axial line as the main base for spatial measurement. Recent innovations by Turner (2001), Dalton (2003), Raford et al, (2005), Hillier and Iida (2005) and Turner (2005) have found segment based angular analysis to correlate better with pedestrian, cyclist and vehicular movement in most cases. Accessibility is a broad concept encompassing proximity and legibility analysis, for a literature review see Halden et al, (2005).

To date Space Syntax vehicular research is located in six areas of inner city London coupled with detailed studies of vehicular flows (397 link counts). The spatial model used was bounded by the North and South Circular Road using more than 16,000 axial lines and 50,000 segment links. Within each area almost every link of local, lower order and primary roads were counted. The areas were urbanised prior to the 20<sup>th</sup> century (Penn et al, 1998, Hillier et al, 2005).

This study used both axial analysis techniques and the “new” angular segment based analysis techniques to explore the effects of transport network layout on traffic levels and compare axial and segment map betweenness and closeness with metric, topological, and angular distance minimisation.

## The Geographical Regional Context

Nantes conurbation is situated in the Loire-Atlantique region of north-west France, south of Brittany. Nantes sits on the banks of the Loire river and at the confluence of Erdre river to the north and Sèvres river to the south. Nantes is the 8th largest conurbation in France with 711,120 inhabitants<sup>1</sup> and covering 476km<sup>2</sup> in 1999. It is one of 14 French conurbations exceeding 500,000 inhabitants. A conurbation is an urban area that includes an urban pole with more than 5000 jobs and areas that are either rural or urbanised where more than 40% of the working population commute to the urban pole. Nantes' main urban pole population is 270,340, and it is the largest regional city. Nantes has 10 other urban poles. To the north, 110 km from Nantes is Rennes. The Rennes conurbation is the 12<sup>th</sup> largest, and it has a total population of 512,200. To the east, 90 km from Nantes, in the direction of Paris, is Angers with an overall population of 332,624.



**Figure 1:**

The map on the left shows the extent of the different conurbations surrounding Nantes. On the right the map shows commuters' location distribution according to the average distance travelled to work. Light grey is less than 14 km, and dark grey is more than 18 km. Note the north, west and south west longest journey locations.

Angers is ranked 23<sup>rd</sup>. To the south east, 65 km from Nantes is Cholet with an overall population of 74,055. To the south, 72 km from Nantes is Roche-sur-Yon with a population of 98,175. To the west, 65 km

**Figure 2:**

The area displayed is the Nantes Urban Community, *Communauté Urbaine de Nantes (CUN)*. The total population for this area is 554,600. The map on the left shows the distribution of population density per ha (10,000 m<sup>2</sup>). The greatest densities are in the 19th century city and beyond, immediately to the south of the river and to some extent in the old village, which has been integrated with the growth of the conurbation. Most of the conurbation has a low homogeneous population density. There are 116 cars per 100 households in the conurbation (left).

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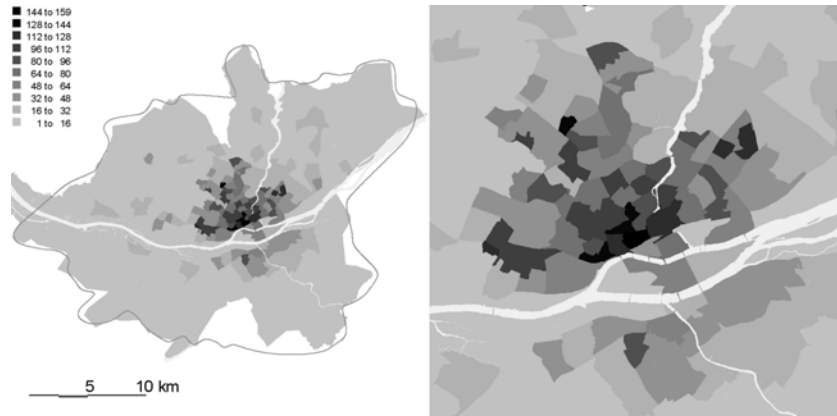
**Conurbation Configuration**

The urban layout of Nantes is overall radio-concentric with half an inner ring on the north side. Nantes has an orbital motorway which surrounds most of the conurbation except to the north west where the urbanised area extends much beyond the orbital. Nantes has the longest orbital motorway (42 km) in France. It allows regional vehicular traffic to cross the Loire estuary. To the north side of the Loire the city has an old centre dating back to the Middle Ages. Urban extensions were built during the 17<sup>th</sup> and 18<sup>th</sup> century with major extensions in the 19<sup>th</sup> and the second half of the 20<sup>th</sup> century. The 19<sup>th</sup> century development reached the north inner ring, while developments in the 20<sup>th</sup> century, mostly a car based urbanism, extended beyond the inner ring and south of the Loire. The urban layout is consolidated. Aerial ortho-photographies (1999), ordinance survey landlines and raster maps were used to establish the axial map of the conurbation. The axial map has about 20,000 axial lines and 60,000 segment links.

**Population Distribution and Activity Distribution**

**Figure 3:**

On the left, economic activities location distribution, each dot represents a company with more than 10 employees. On the left the map shows the location of shops and supermarkets within the Nantes commune only. Note the clustering locations: central, along radials and in close proximity to the orbital (bottom).



## Vehicular Observation Data Set

The vehicular observation data set is made up of 168 vehicular cordon counts from 2001. The counts were made by the Direction Departementale de l'Equipelement, the equivalent of the local Highway Agency that manages and maintains main roads. All cordon counts were located on two-way roads. The cordon counts are automatic traffic recorders, whether static count stations (33) or mobile count stations (135). Static count stations average out 15 minute counts to a daily average. These daily averages are used to create a yearly daily average. Static stations are used to monitor traffic in real time. The static stations were located on motorways and national roads and bridges.

Similarly, mobile counting stations usually monitor traffic for a week at a time, several times a year. The daily averages are established as with static stations.

Most of the cordon counts are made on two-lane roads (103) and four-lane roads (41) the remaining are three-lane roads (3) five-lane roads (9); and six-lane roads (3). The direction split was not made available. Some of the counts fall out of the spatial map.

### Two-lane roads – daily vehicle flow levels

Daily vehicles	850-5,000	5,000-10,000	10,000-15,000	15,000-20,000	20,000-33,000
2 lanes road	39 – 36%	31 – 28%	18 – 16%	14 – 13%	10 – 9%
Useable width	5 – 7 m	5.5 – 8 m	6 – 7.5 m	6.5 – 8 m	7 – 7.5 m

The two-lane roads have a useable width that varies between 5 and 8 meters. The flow levels varied between about 1000 vehicles/hour to 33,000. While the maximum road width varied by 60% from the minimum, the flow levels varied by up to 33 times. Although a linear fit between road width and daily vehicle level results in  $r^2 = 0.37$   $p < 0.001$ . As most of the roads were either 6 meters (39) or 7 meters (38) wide, the variations around these two widths cannot be explained by road capacity variations alone.

### Four-lane roads – daily vehicle flow level

Daily flow	15,000-30,000	30,000 – 45,000	45,000 – 60,000	60,000 – 75,000	75,000 – 90,000
4 lanes road	12 – 29%	14 – 34%	6 – 15%	7 – 17%	2 – 4%
Usable width	12 – 15 m	12 – 15 m	14 – 15 m	14 – 16 m	14 m

The four-lane roads have a useable width that varies between 12 and 16 meters. The flow level varied between 15,000 and 90,000 vehicles/hour. While the maximum road width varied by 33% from the minimum, the flow level varied by up to 6 times. No relationship could be established between road capacity and vehicle flow ( $r^2 = 0.02$ ).

## Vehicle Dynamic, Network Morphology and Flow Rate

The vehicle observation data set has been established for different types of roads: motorways (up to 6 lanes), national roads (up to 4 lanes) and local roads (2 lanes). We briefly review the literature on the relationship between road types, vehicle dynamic, network morphology and flow rate.

When observing traffic on a motorway and plotting the traffic flow (vehicles/hour) versus the traffic density (vehicles/kilometre/lane) for a location along the motorway, a curve as in Figure 7 occurs. This curve has a characteristic shape that is very similar for every motorway section and is known in traffic literature as the fundamental diagram. For zero traffic density (no cars on the motorway), the traffic flow is zero. With increasing traffic density (more vehicles on the motorway),

**Figure 4:**

The map shows the traffic distribution in Nantes conurbation (Auran, 2001). Vehicles per day are reflected in the thickness of the dark grey lines. The thickest dark grey lines represent more than 50,000 vehicles/day, then 40,000 to 50,000, 30,000 to 40,000, 15,000 to 30,000, 5,000 to 15,000 while the thin dark grey lines represent less than 5,000. The light grey shows the road network (top-right)

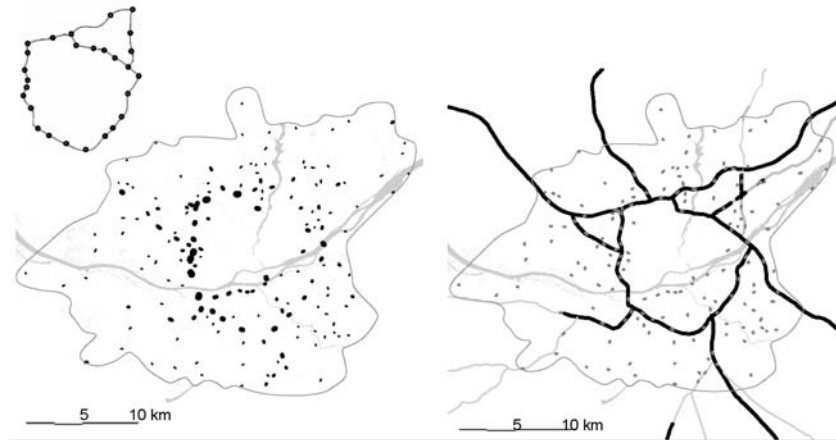
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the traffic flow also increases. However, if the traffic density increases further, the increase of the traffic flow will slow down sooner or later. At a certain point, the flow reaches a maximum density called the critical density  $C_{cr}$ . The traffic flow on the motorway decreases with increasing density if this is greater than the critical density. Eventually a tipping point is reached and the flow becomes zero again. This is defined as density  $C_{jam}$ .



**Figure 5:**

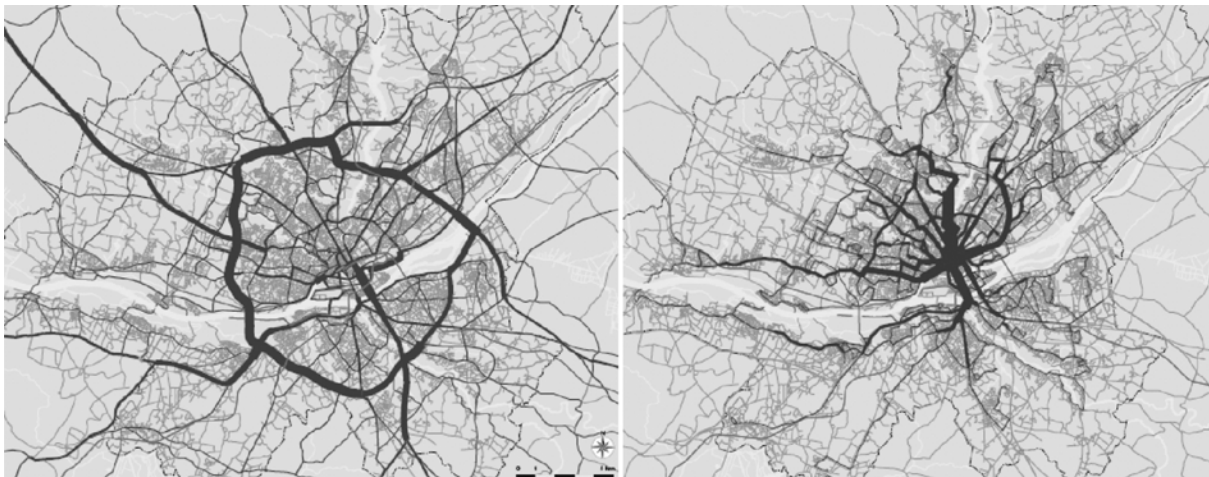
On the left the location of all cordon counts (168) according to daily flow rate with different size black dots indicating the flow rate. The light grey continuous line marks the extent of the axial map covering 570km<sup>2</sup>. The central city area has almost no data (66 km<sup>2</sup>). Note the intensity of the flow on the orbital north, west and south west side. On the right cordon count locations are indicated as light grey dots in relation to the road hierarchy: thick black and grey lines are four to six-lane roads all others are two-lane roads. In insert the orbital and its junction locations (middle)



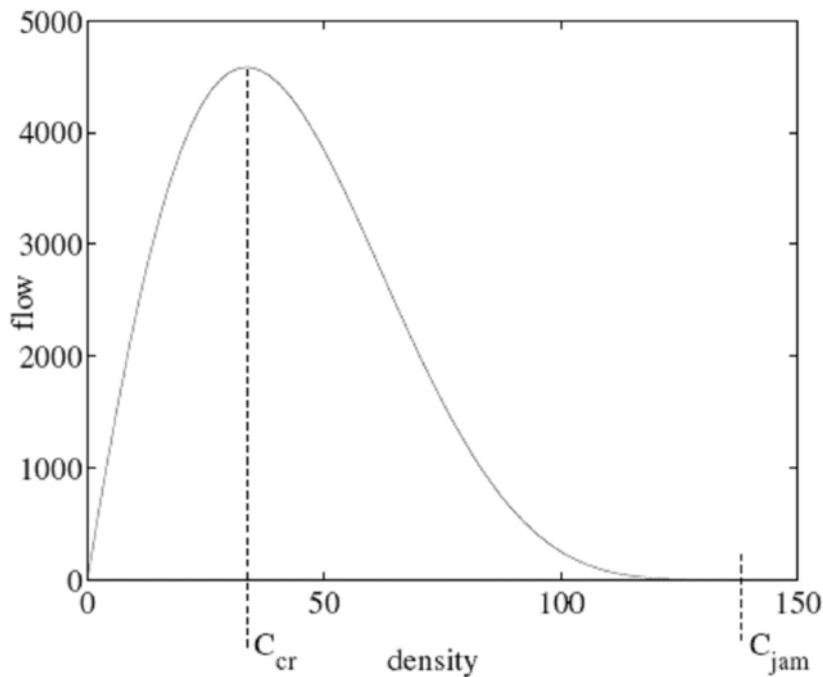
**Figure 6:**

The maps show the dual travel pattern of vehicular travel on the left and public transport travel on the right (Auran, June 2004). The thicker the dark grey lines the higher the use intensity (bottom)

Vehicle/day	800 - 18,300	18,300 - 35,800	35,800 - 53,300	53,300 - 70,800	70,800 - 88,100
Number of count	101	35	13	13	6







**Figure 7:**

The fundamental diagram showing the relationship between speed density and flow rate. A plot of traffic flow versus traffic density on a motorway results in the figure below. The density at which the traffic flow is maximal is called the critical density  $C_{cr}$ . The (non-zero) traffic density at which the flow equals zero (i.e. the traffic grinds to a halt) is called the jam density  $C_{jam}$ .

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The behaviour of traffic on a motorway and the fundamental diagram can be interpreted as follows: when the traffic density is zero, the traffic flow will be zero as well. When the traffic density starts to increase (more cars are travelling on the motorway) the traffic flow increases. In low traffic densities, the relationship between flow and density is almost linear due to the only minor interaction between the vehicles. As the traffic density increases, the interaction between vehicles increases rapidly. E.g. fast cars will have to slow down while waiting to overtake a slower car. Due to the decreasing average speed with increasing density, the traffic flow increases at a slower and slower rate. The traffic flow reaches a maximum for the critical density  $C_{cr}$  after which the flow decreases again with further increasing traffic density. In high-density traffic situations, drivers tend to slow down, resulting in a drop of traffic flow, even though the traffic density is high. The maximum possible traffic density on the motorway is  $C_{jam}$ , the density at which the vehicles come to a halt: if a vehicle stops, the upstream vehicles are forced to stop as well.

On ordinary two-lane highways passing vehicles must use the oncoming lane. Passing demand is a consequence of speed differences between vehicles. Passing opportunity is supplied when there is long enough headway in the *oncoming traffic* and long enough *sight distance*. If vehicles cannot pass slower vehicles without delay, platoons begin to form. Platooning increases the proportion of short headways and decreases mean speed and flow rate. In front of slow vehicles there are empty zones, which cannot be used effectively. This reduces the capacity and the flow rate of two-lane highways Salter (1981).

Speed potential is affected by connectivity (junctions) and network geometry. Both connectivity and highly contoured network geometry may affect traffic flow by causing vehicles to slow down, while very straight and long lines permit constant high speed and higher flow rate. The faster one can drive without difficulty the straighter is the network geometry. On two lane roads overtaking requires a longer straight stretch for visibility of the oncoming traffic and the length to accelerate, overtake and return. There is congruence between network geometry (connectivity, straightness continuity, capacity) and flow rate. The interplay between connectivity and straightness continuity may have an impact on driver preference and needs to be captured by the

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network analysis. An analytical unit could be the number of junctions by stretch of straight road length. In transport network analysis, the spatial unit is a link, the stretch between two junctions independently directness continuity, The aspect of directness continuity is not analysed probably in part because in the network graph theoretic encode the junction being the node and the edge the link, the encoding emphasis is on mapping the local locus of potential decision point and discontinuity, the junction, more than directness continuity perception that provide a more global decision making. Marshal, (2005) has proposed such a directness and connectivity encoding, without performing empirical tests.

The axial map encoding of the network geometry allows for this analysis as the axial line is the unit of spatial straightness/continuity and axial connectivity is the number of other lines connecting to it.

### Network Configuration and Flow Rate Analysis: Findings

The data was analysed in three phases. The first phase separated two-lane roads from three to six-lane roads. The second phase analysed the whole data set. For both phases the approach was to use an axial line map and a segment map and compare metric, topological and angular distance closeness and betweenness and explore any other relationship conducting simple regression and multivariate analysis between spatial variables and daily vehicle counts. The third phase analysed the whole data set using multivariate data analysis to try to achieve the best correlation. The data set was normalised by natural log and Box Cox transforms. All spatial analyses was conducted using UCL Depthmap 6.0824r, Turner (2000-2006). Statistical analyses used SAS JMP 5.1.

#### Two-lane Roads

Significant correlations were found between daily counts and spatial variables. Weighting spatial variables with axial line length does not yield any significant increase in correlation levels. The highest correlation is found with topological distance closeness ( $r^2$  adj. = 0.56), followed by segment angular distance closeness ( $r^2$  adj. = 0.55), and segment metric distance closeness ( $r^2$  adj. = 0.42).

#### Two-lane roads

$r^2$ adj.	metric distance		topologic distance		angular distance	
$p < 0.0001$	betweenness	closeness	betweenness	closeness	betweenness	closeness
Axial line	na	na	0.28	0.56	na	na
Segment	0.20	0.42	na	na	0.28	0.55
<i>Nb of counts:</i>	98		<i>Sum of daily vehicle count: 904,230</i>			

Adding road width to axial topological closeness increases the correlation to  $r^2$  adj. = 0.63  $p < 0.0001$  with a t ratio twice as much for closeness than road width.

#### Two-lane roads, spatial variables weighted by axial line length

$r^2$ adj.	metric distance LW		topologic distance LW		angular distance LW	
$p < 0.0001$	betweenness	closeness	betweenness	closeness	betweenness	closeness
Axial line	na	na	0.23	0.56	na	na
Segment	0.23	0.41	na	na	0.29	0.55
<i>Nb of counts:</i>	98		<i>Sum of daily vehicle count: 904,230</i>			

The axial topological closeness positively correlates with segment angular closeness  $r^2$  adj. = 0.87  $p < 0.0001$ . No meaningful correlation was found between connectivity, line length and axial closeness  $n$ , or daily counts.



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**Figure 8:**

The map shows the topological closeness  $N \log$  transform. The lowest values (20%) are highlighted in thicker black lines. Note the radio concentric organisation, the spatial characterisation of the central 19th core, the radial main roads, the orbital and motorways.

**Three to Six-lane Roads**

No meaningful correlation was found between daily counts and spatial variables.

**Three- to six-lane roads**

$r^2$ adj.	metric distance		topologic distance		angular distance	
	betweenness	closeness	betweenness	closeness	betweenness	closeness
Axial line	na	na	- 0.001 $p = .3482$	0.09 $p = .0143$	na	na
Segment	0.12 $p = .0041$	0.16 $p = .0010$	na	na	0.10 $p = .0101$	0.10 $p = .0130$
Nb of counts:	58		Sum of daily vehicle count: 2,638,366			

**Three to six-lane roads, spatial variables weighted by axial line length**

$r^2$ adj.	metric distance LW		topologic distance LW		angular distance LW	
	betweenness	closeness	betweenness	closeness	betweenness	closeness
Axial line	na	na	0.007 $p = .2426$	0.12 $p = .0050$	na	na
Segment	0.15 $p = .0014$	0.18 $p = .0006$	na	na	0.12 $p = .0049$	0.08 $p = .0169$
Nb of counts:	58		Sum of daily vehicle count: 2,638,366			

Surprisingly, a significant negative correlation between daily counts and axial entropy were found. We investigated this spatial measure with two lane-roads and all roads, the results are as follows:

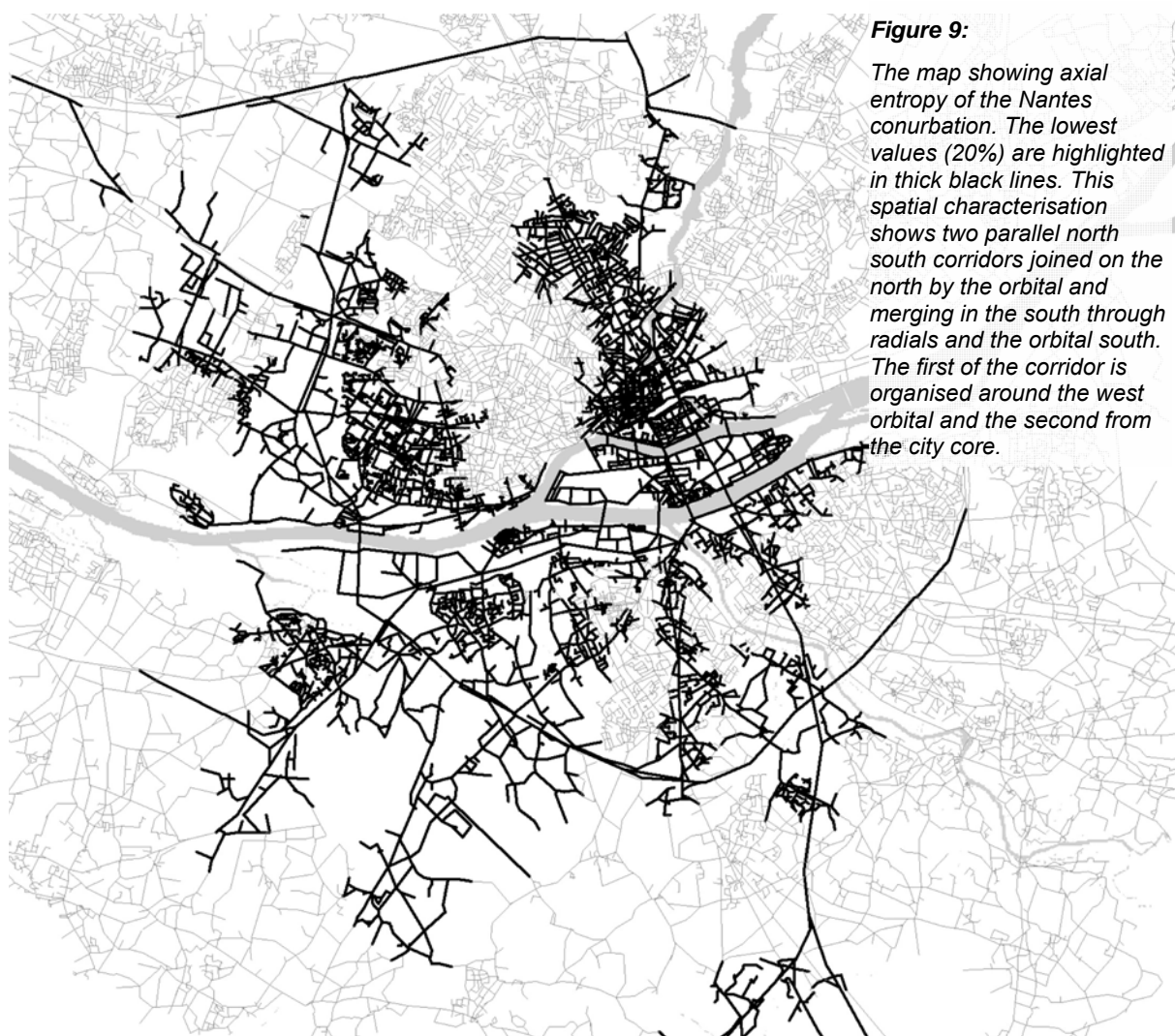
- 3 to 6 lanes  $r^2$  adj. = 0.44  $p < .0001$  (Y Box Cox transform)
- 2 lanes  $r^2$  adj. = 0.31  $p < .0001$  (Y Box Cox transform)
- All roads  $r^2$  adj. = 0.45  $p < .0001$  (Y Box Cox transform)

No meaningful correlation was found between connectivity, line length and axial closeness N, or daily counts.

The correlations between axial connectivity and axial line length was investigated, the results are as follows:

- 2 lanes  $r^2$  adj. = 0.61  $p < .0001$
- 3 to 6 lanes  $r^2$  adj. = 0.41  $p < .0001$
- All roads  $r^2$  adj. = 0.36  $p < .0001$

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**Figure 9:**

The map showing axial entropy of the Nantes conurbation. The lowest values (20%) are highlighted in thick black lines. This spatial characterisation shows two parallel north south corridors joined on the north by the orbital and merging in the south through radials and the orbital south. The first of the corridor is organised around the west orbital and the second from the city core.

### **All Roads**

Significant correlations were found between daily counts and spatial variables. Weighting spatial variables with axial line length does not yield any significant increase in correlation levels. The highest correlation is found with topological distance closeness weighted by axial line length ( $r^2$  adj. = 0.64), followed by segment angular distance closeness ( $r^2$  adj. = 0.63), and segment metric distance closeness weighted by line length ( $r^2$  adj. = 0.44). The use of varied

combinations of multivariate analysis did not bring better correlation results, except by using useable road width which gives  $r^2$  adj. = 0.84  $p < 0.0001$  with almost equal t ratio for road width and topological distance closeness weighted by axial line length.

### All roads

$r^2$ adj.	metric distance		topologic distance		angular distance	
$p < 0.0001$	betweenness	closeness	betweenness	closeness	betweenness	closeness
Axial line			0.36	0.63		
Segment	0.18	0.43			0.30	0.63
<i>Nb of counts:</i>	156		<i>Sum of daily vehicle count: 3,542,596</i>			

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### 9.3.2 All roads, spatial variables weighted by axial line length

$r^2$ adj.	metric distance LW		topologic distance LW		angular distance LW	
$p < 0.0001$	betweenness	closeness	betweenness	closeness	betweenness	closeness
Axial line			0.41	0.64		
Segment	0.30	0.44			0.39	0.63
<i>Nb of counts:</i>	156		<i>Sum of daily vehicle count: 3,542,596</i>			

The axial topological closeness positively correlates with segment angular closeness weighted by line length  $r^2$  adj. = 0.91  $p < 0.0001$ . The segment metric distance closeness positively correlates with segment metric distance closeness weighted by line length  $r^2$  adj. = 0.998  $p < 0.0001$ .

No meaningful correlation was found between connectivity, line length and axial topological closeness N, or daily counts.

### Discussions

The findings both differ and agree with previous vehicular space syntax studies. Penn et al, (1998) found that the highest fit was with an axial map topological distance radius three and decreasing when radii were increasing. We found that, on the contrary, the best fit is found by increasing radii up to N. Penn's study best fit was achieved using useable width for primary and secondary roads separately and all roads together while in our study useable road width seems to play a minor role with the secondary route, no role with the primary route and the expected trend of increasing traffic flow in roads with more lanes. Generally, as road width increases flow levels are higher in relationship to road hierarchy as in Penn et al (1998). These differences can be understood in relationship to the regional scale of the road we have studied, the vehicular traffic spatial interaction at conurbation level.

The findings of Hillier and Iida (2005) in four inner city London areas does not distinguish primary from secondary roads, nor investigate the impact of useable road width. Systematically topological and angular measures are better than metric measures without any of the two being generally the best fit, while in our research these two measures give the same levels of correlation for the secondary routes and the overall set, yet do not account for traffic flow on primary routes (motorways) where axial entropy is playing a significant role.

Turner (2006) using one of the four areas (Barnsbury), previously analysed by Hillier and Iida (2005), has argued that betweenness should form a better model of movement data than closeness as it is interpreted in direct proportion to observed values. One of the main tenets of Turner is to weight betweenness with segment length arguing that a longer segment should generate more trips, while recognising

that this would not be the case for a motorway. In our research axial and segment closeness is outperforming betweenness. Our contentions are that we should prefer a generic hierarchy interpretation of betweenness levels instead of a direct account of journey level and proportion of traffic flow and that the importance of segment length could be simply interpreted as the result of vehicle dynamic and driver preference, where the driver prefers straight continuous lines and speed over short segments, junction slow down and turning fatigue. This applies especially in inner city configurations where there is high correlation between line length and higher connectivity level.

Overall our findings remain interpretable within the spatial cognition framework laid out in Hillier and Iida (2005) and previous papers relating space syntax analysis to spatial cognition and urban environment legibility. The only exception is the role of axial entropy in relation to primary roads. As axial entropy increases on primary roads, vehicular flow decreases. Reference to entropy and in particular to entropy maximisation was standard in transport and large scale regional models. The rationale for entropy maximisation can be found in Wilson (1967) and a vast body of transport research literature. More recently, Wilson (2000) proposes that if we are interested in bundling journeys into an emerging pattern rather than concerning ourselves with the individual journey then it can be shown that the probability of a pattern of bundle journeys occurring, is proportional to the number of ways in which individuals could be arranged in bundles or groups to produce that emerging pattern. In other words, overall route choice pattern is in direct proportion to the probable patterning of individual route choice preferences.

Combinatorial theory shows that this number can be calculated for particular patterns. The most probable pattern can then be derived by maximising the entropy function. Wilson goes on to propose the following interpretation: people are behaving as though they perceive travel costs to be increasing logarithmically. For example, we might expect that if journeys are generally short, then people will perceive travel cost to be linear. If journeys are much longer, as in a regional system, then people may be less worried about adding further to longer journey paths, and a power function might fit better. This interpretative framework is within the standard assumption that route choice is a function of distance-time minimisation. Within a spatial cognitive and informational framework and the new network theory literature this might need a complete revisit.

In space syntax entropy is a global measure based on the frequency distribution of closeness (Turner, 2001). A measure of entropy is a measure of the *distribution* of locations in terms of their closeness from an axial line rather than the closeness itself. Calculating axial entropy can give an insight into how ordered the system is from a location. Adapting an example from Turner: if a motorway is connected to a main road then there is a marked disorder in the axial closeness from the point of view of the junction. At closeness 1 there are only a few locations available from the junction, then at closeness 2 there are many locations from the road, and then order contained within further levels will depend on how the junction is integrated within its environment (see Turner, 2001, for a more detailed discussion). So, if many locations are close to an axial line, the axial entropy from that line is asymmetric, and the entropy is low. If the closeness is more evenly distributed, the entropy is higher. Turner notes that there is a spatial interpretation problem for entropy and that is that entropy is low for uneven distributions, whether these are close *or far* away from the current axial line. Entropy corresponds to

how easy it is to traverse to certain a closeness level within the system.

It is suggested that if we reverse Wilson's further metric distance assumption, it might then be more appropriate to legibility Hoon (2005) - as the overall journey length increases people not knowing the network well, will seek to minimise the journey route choice complexity. Journey repetition, as in commuter travel, might further increase distance while minimising complexity or not. As we discussed above, there is congruence between transport network design for speed and linearity and choice minimisation by designing fewer junctions and consequently reducing connectivity. There is the potential that the primary network, while being very simple to comprehend in its overall form prior to travel, might, while on route, from some point be difficult to access or exit because of the lack of connectivity and the possible complexity of access/exit into and from the wider secondary network which in its own right has its own particular level of complexity. This distribution asymmetry is what entropy would capture. In the context of the regional role of the primary network in this study, axial entropy can give an insight into how the spatial configuration of the transport network facilitates or hinders navigation ease continuity, i.e. facility continuity: while low disorder is easy to navigate, high disorder interface between the primary and the secondary network can make route choice much more difficult and lead to prefer much longer journey distance. As excess commuting seem to suggest there is a general sub-optimal use of distance minimisation, perhaps to be explained by a low disorder optimisation.

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Clearly, at conurbation level, we can no longer assume that drivers know the entire transportation system in the conurbation area and simply choose the least-distance or least-time path. If drivers choose their routes based on travel time and/or other considerations, such as minimising the difficulty of the driving task or maximising facility continuity, but if an ATIS suggests routes based on travel time only, the ATIS will not suggest routes that drivers would consider the most attractive. Instead, algorithms that generate more "human-looking" routes would have greater usefulness and appeal to ATIS customers.

We have shown that the space syntax spatial analyses identifies reasonable routes that drivers may consider making her or his choice at emergent level and could generate choice probability as a function of spatial attributes of the network. This study suggests that the impact of network spatial knowledge and legibility has been underestimated and could provide a way to enrich ATIS and discrete choice model with a certain level of behavioural realism Walker (2001) and Waker and Ben-Akiva (2001). Axial entropy may give inroad into understanding behavioural aspect of induced-disappearing demand in relation to capacity increase-reductions Cairns et al. (1998) resulting in congestion decrease-increase and its levelling off.

To our knowledge axial entropy empirical study is a new phenomenon in space syntax literature, much more research is needed to further explore the full impact of axial entropy in this study and in different road networks. For a deeper understanding we will need to:

- characterise and understand more precisely the differentiation of value assignment regime between axial entropy versus axial or segment closeness and betweenness.
- collect detailed information examining the effects of various factors on route choice by both direct observations on the route choice behavior other than the traffic counts. Traffic counts have little information on individual route choice but are good indicators of

emergent journey patterns resulting from individual spatial knowledge, and way finding propensity interacting with the transport network and OD. Yet, the collection of the detailed information on driver's route choice behavior alone, however, is not sufficient to provide a better understanding of route choice behavior, Raford et al. (2005).

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i. All population references are from the 1999 census