A Simplified Route Choice Model Using the Shortest Angular Path Assumption

Alasdair Turnerand Nick Dalton

Bartlett School of Graduate Studies, University College London
Gower Street, London, WC1E 6BT
Tel: +44 20 7679 1806
Email: a.turner@ucl.ac.uk, n.dalton@ucl.ac.uk

Abstract

Route choice within transportation network analysis is generally assumed to correspond to a utility function. Although cognitive factors are known to affect this function, most route choice models assume that minimum time or distance are the primary elements affecting the chosen path. However, evidence from cognitive science suggests that the number and angle of turns during a pedestrian journey affects the perception of its length. Does this distorted estimation affect drivers' route choice? In this paper, we build a model which assumes drivers will try to take the minimum angular path rather than the more usual minimum block-distance path. In order to concentrate on the cognitive choices involved, we use a simplified model. We form a network from standard road-center line data. The lines comprising the network are treated as a graph, where each straight-line segment acts as a node, and the edge-weight to any other segment is the angular turn to it from the current segment. To allocate trips, every segment is treated as a both a possible origin and a possible destination, and we assume the shortest angular path between the two is followed. This allows us to use the standard graph measure of betweenness to act as an approximation of relative vehicular flow through segments. We validate the model against daily traffic-flow rates collected for a small region of London in a previous study. We find that the minimum angular path model correlates strongly with observed traffic flows, and that it significantly outperforms a minimum block-distance model.

1. Introduction

Route choice models tend to assume people adhere to an underlying utility function when selecting a route. That is, there is an internal process which assesses the costs of various aspects of the journey ahead, and picks the journey with the minimum cost and maximum utility. Different people will value different things on a trip, for example shorter trip length, more time on a freeway, fewer left turns and so on (Ben-Akiva et al, 1984). Thus, the utility function is assumed to be a complex item comprising many factors. In addition, different people will have different levels of knowledge of the network, so their understanding of possible routes is an issue; furthermore, the modeler's own appreciation of the individual's utility function is limited. In order to account for these differences, models introduce restricted choice sets to handle knowledge deficiencies in drivers, and randomized utility functions to handle deficiencies in modelers (for a review see Bell and Iida, 1997; Ben-Akiva and Beliere 2003). These innovations have led to a proliferation of complex route assignment algorithms, from simple shortest paths, through to variations on probit and logit models. Each one assesses the probability that, due to perceptual differences, a driver is likely to take a specific route through the network. At their most simple, these might exclude routes that take the driver away from the destination (Dial, 1971), or modify the available routes (Tversky, 1972). At their most complex, a series of utility factors is brought together as an equation according to perceptual qualities of the route and learnt behavior of drivers (e.g., Nakayama et al, 2001; Cascetta et al, 2002).

Nevertheless, in all these models the utility function tends to be based on observable quantities of the street segments themselves: their length, their congestion, their traffic calming obstructions, their scenery and so on. This is, of course, common sense. However, it seems that a fundamental issue has been overlooked in this common sense assumption: the driver's own perceptual and cognitive understanding of the street network. At first, this statement seems contradictory: surely this is exactly what Nakayama et al's and Cascetta et al's models attempt to compensate for? This is correct, but their models and others adjust the *parameters* of the utility function, not the *components* that comprise it. That is, the shortest path as perceived may not actually be the 'common sense' shortest path that we calculate in block distance. Therefore we cannot simply fade in and out shortest path, but must actually work out what shortest path means to the person involved. Indeed, perceived times and distances are often significantly distorted from the physical factors involved (Tversky, 1992). This variation seems to be reflected when geographic positioning system (GPS) traces of real vehicular movement are recorded: the paths that are taken are not the 'shortest' (Jan et al, 2000).

So what is the individual's conception of distance? Montello (1991a) summarizes two categories of distance: cognitive distance concerns people's beliefs about distance where the destination cannot be seen; perceptual distance concerns beliefs about directly observable destinations. Note that 'belief' is used in place of estimate, as 'estimate' involves the communication of the belief to the experimenter. Note also that how people drive through a street network may not necessarily use one or the other. We tend to think of route choice in terms of cognitive distance, but what is to say that a driver does not in fact make impulse, perceptually-based, decisions as they drive from origin to destination? For the time being, let us consider cognitive distance, as it has more implications for the method we shall choose. At first sight, cognitive distance appears to be inconsistent: primarily, it is guided by heuristics (Hirtle and Gärling, 1992); further, it seems to be distorted towards known landmarks (Sadalla et al, 1980); it also appears to depend on where one starts, as in pedestrian route choice experiments, people take different routes according to whether they are going from origin to destination or destination to origin (Golledge, 1995). In addition, and relevant to us, it appears to be more affected by the actions involved between origin and destination than the effect of the intervening physical distance. Sadalla and Magal (1980) asked people to estimate the length of different pedestrian journeys. They found that people found trips shorter if they had fewer turns, even if the physical distance covered was longer. Thus, Sadalla and Magal propose the segmentation hypothesis: that people divide a route into segments, where each segment is simply perceived as a single journey element of indeterminate length, but the turns themselves are remembered. In driving, it might be supposed that the effect may be even more pronounced, as the general action of forward movement requires such little effort. Thus, this theory leads therefore leads to a hypothesis for transportation network analysis: is it possible to create a discrete choice model based on the number of turns required in a journey?

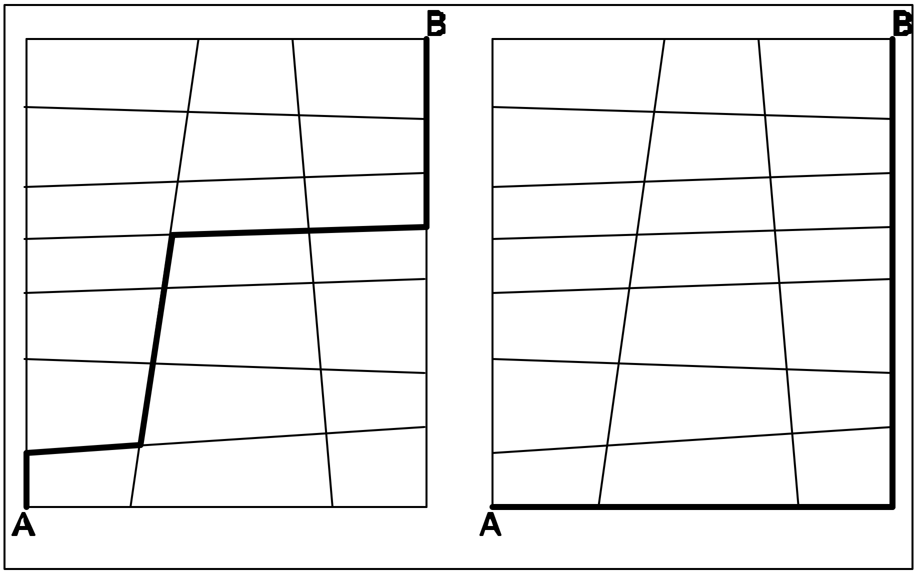

Figure 1. Left: a shortest block-distance path from A to B. Right: a fewest number of turns path from A to B. In segmentation theory, the fewest number of turns path is cognitively shorter.

In fact, the reverse operation has already been considered, when it comes to the construction of driver navigation systems. Ramming (2002) identifies the need for more "human like" routes to be suggested to the driver. Duckham and Kulik (2003) propose that the minimum angular path might be useful to help direct drivers to their destination more simply, with a demonstrative system (an example in the difference between shortest block-distance path and shortest angular path is shown in figure 1). Herein, as per Duckham and Kulik, we implement a system that generates shortest angle routes between origin and destination. The methodology we use is based on the theory of space syntax (Hillier and Hanson, 1984), and thus we make several differences to the usual implementation and testing of such systems. Firstly, the system itself reverses the usual conception of nodes and links, so the road segment becomes the node, and the junction the link. This facilitates thinking of routes in terms of number and angle of turns rather than straight-forward distances. Secondly, our experiments are based on a simple graph measure, which allows us to concentrate on the effect of changing the shortest path component of the utility function to a shortest angular path component, in isolation of the usual economic and demographic considerations that surround analysis of the transportation network. That is, we are interested in the effect of the network configuration *ceteris paribus*, rather than constructing a realistic traffic model. Thirdly, and finally, our validation reflects an observation by Cadawaller (1979): 'An individual's distance estimate is not independent of the methodology used to obtain that estimate.' (p. 563). Therefore our validation is based not on what people report about their route choices. Neither is it based on analysis of individual trips, due to the difficulty of retrieving large amounts of route choice data (Montello, 1991a)[1]. Instead, we look

[1] Although note that access to GPS data such as that collected by Jan et al (2000) is rapidly making this sort of analysis more feasible.

at secondary evidence — the outcome of the route choices taken sampled various 'gate' locations within a small area of the network — and compare the predicted relative flow rates with observed flow rates.

The paper begins with a discussion of the space syntax background to the technique in the next section, followed by a section on methodology, one on validation, and finally a discussion of the implementational details before concluding.

2. Background

The effect of configuration on the movement of both pedestrians and traffic has seen significant research outside the usual domain of transportation network analysis, in the field of space syntax (Hillier and Hanson, 1984). Space syntax follows most network analysis in that it translates a network map into a graph, and then a graph analysis is performed to determine movement potentials at individual nodes. However, there are two main differences. Firstly, the network is drawn as a series of 'longest lines of sight' called *axial lines*. Secondly, rather than treating the junctions of these lines as nodes, the lines themselves are treated as nodes, and the junctions as links. The simple expedient of reversing the normal mapping of nodes and links means that a graph analysis compares the number of turns from one line to any other line. Therefore, space syntax would seem to correspond to a route choice implementation of Sadalla and Magal's segmentation theory, in that turns increment the cost of a journey whereas straight-line segments do not.

Nevertheless, there are a several problems with raw space syntax. The first is the near mythological significance of axial lines in space syntax (at least to those observing from outside the field). Long straight-lines are required as breaking one at a junction would result in a 'turn' being recorded. As a corollary to the segmentation theory, this is known in space syntax as the *segmentation problem*. However, merely having long straight lines does not help if there is a slight curve in the road: this still requires another axial line, and thus leads to a 'turn' being recorded where a person would probably ignore the turn (although some researchers straighten these in a nod to representing the cognitive distance). In an effort to resolve this issue, Dalton (2001) introduces *fractional analysis*, where the intersection angle is considered as the dot product of the two lines. Two lines at right angles make a turn, whereas two almost parallel lines have a low fractional weight attached to them. This, though, is still problematic where there really exists a sharp turn one way or the other. Thus, Turner (2001) introduces *angular segment analysis* (ASA) to space syntax. In this model, the lines are split into a more conventional network, where junctions and turns break the lines into segments. The cost of transfer from one segment to another is treated as the angle from one segment to another. This does have the associated loss of the direct cognitive mapping — in fact, people tend to split angles into a few major divisions (Montello, 1991b) — but it does allow for simple angular analysis of segment networks. It also follows recent developments in cognitive science, where the least-angle strategy has been implemented for agent-based experiments on human cognition (Hochmair and Frank, 2002) and forms the basis of Conroy Dalton's (2003) 'British Library hypothesis', which states the heuristic that people will try to direct themselves according the (perceived) current minimum angle to the destination. However, if we refer back to figure 1, it is obvious that such a heuristic yields a different result again to those shown, with the occupant moving due North until a turn to the East would decrease the angle to B, yielding a path somewhere in between the shortest block-distance path and the shortest angular path. Our own observation of the diagram suggests that the version on the right still seems a more intuitive response.

In support of the theory, angular segment analysis of axial networks has recently been shown to correspond well with movement of both pedestrians and vehicles (Hillier and Iida, 2005). However, there is a further problem of long straight lines (especially where they may have been straightened): they acquire the same graph analytic value along the length of them. In the case where a line is 5km long (about 3 miles), the theory simply does not stand up for pedestrian journey analysis: although pedestrians may associate cost more with turns than physical distance, they cannot possibly treat a 5km walk as zero cost! Even in a car journey, long roads without junctions will still be treated as having some impact on the journey. Thus, we need some way to take into account real journey lengths, and the real nature of the underlying network. Herein, we include trip generation as a parameter, and simply replace the axial network with road-center lines. In addition, we attempt to resolve a further question that space syntax has largely ignored: is the fewest number of turns actually a better predictor of route choice than simply taking the shortest block distance path?

3. Methodology

In this section we describe the mechanics of our system for testing the shortest angular path assumption using angular segment analysis (ASA). The system under consideration is imported into a graph analysis package[2] as road-center line data, which is easily obtained in many countries. For the experiments described here we imported the UK's Ordnance Survey Land-Line data directly into the system. We then connect the segments together as a graph weighted by the intersection angles with other segments[3]. In order to construct shortest angular paths between the segments, we need to realize that this is not a standard graph. We need to take the direction of entry to a segment into account, so that a journey cannot double back along a segment at zero cost, to take advantage of a shallow angle link, as shown in figure 2.

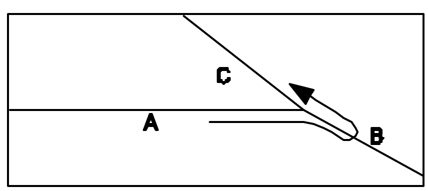

Figure 2. The segment graph uses directed nodes, so that segment A cannot link to segment C through segment B without turning through 180 degrees.

To achieve this directionality in our implementation, we simply separate the links from each segment into 'forward' and 'back' edges, where the 'forward' and 'back' ends of the segment

[2] See the section on Implementational Details for more information about the software and hardware used.

[3] Care needs to be taken to ensure that segments do not accidentally connect where a road passes over another road, for example, in the case of a freeway flyover.

are assigned at random. If a segment is entered via a back link, then it may only connect onto forward links and vice versa. Thus in effect, we have two directed graphs overlaid on top of one another. This may seem like a draw back to using segment nodes rather than junction nodes; however, in a junction node graph, we would still need to consider three nodes to form an angular calculation, so the difference is in fact minimal.

Once the graph has been constructed, we use a simple trip generation algorithm: every segment is regarded as both an origin and a destination for journeys, so an all-to-all matrix of origins and destinations is constructed. However, in order to account for both trip length, and to stop edge effect in our modeled area (where trips from a segment come to a stop against the edge of the modeled area), we set a maximum limit on the block distance from origin to destination, and use it as a parameter to the system. We then allocate trips according to the shortest angular path from origin to destination. In order to account for differences between the number of trips generated very long segments and very short segments, the number of trips is weighted by the length of the origin segment and the length of the destination segment. This calculation results in a weighted version of the graph measure of betweenness (Freeman, 1977) shown in equation 1, where N is the number of segments in the graph, $l(x)$ is the length of segment x, and $d(x,y,z)$ is a delta function of x, y and z, which equals 1 if the shortest angular path from x to z goes through y, and 0 otherwise. The weighting ensures that however segments are broken up by the cartographer when drawing the map, the overall measure remains the same.

$$B_w = \sum_{p=1}^{N}\sum_{q=1}^{N}\sum_{r=1}^{N} l(p)l(r)d(p,q,r) \tag{1}$$

We further enhance this equation to account for the beginning and ends of journeys (the parts on segment p and r in equation 1). The situation is shown in figure 3:

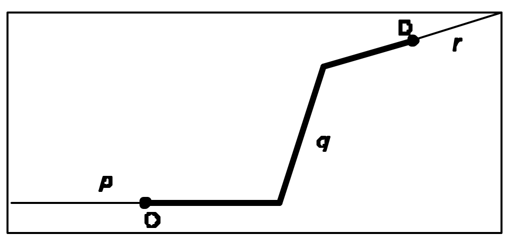

Figure 3. Trips are considered to start and finish midway along a segment.

Obviously a trip from O to D will pass through q fully, and along partway of segments p and r. For convenience, we assume that half the starting segment and half the ending segment will be included in the journey, and thus change the function $d(x,y,z)$, so that it is 0.5 if $x=y$ or $y=z$ (i.e., the segment under consideration is the starting or finishing node), including the case of $x=y=z$, where the segment acts as both the origin and the destination.

One interesting outcome of the decision to weight the values by length of lines is that the graph measure now has units: we find that weighted betweenness is most easily expressed in km^2, although obviously there is no inherent significance in this unit.

4. Validation

In order to validate the hypothesis that minimum angular routes will be favored over minimum block distance paths, we took observation data from a previous study by Penn and Dalton (1994). Penn and Dalton observed vehicular movement within the residential urban area of Barnsbury, in North London. They give average hourly and daily vehicular counts at 112 'gates' located at almost every inter-junction segment within a $1km^2$ area. We imported road-center lines for this area and a 1km buffer around it, as shown in figure 4. Figure 4 also shows betweenness values (B_w) for the angular analysis of the system for radius 2000m, that is, for all-to-all journeys for segments up to 2000m apart from each other in terms of block-distance.

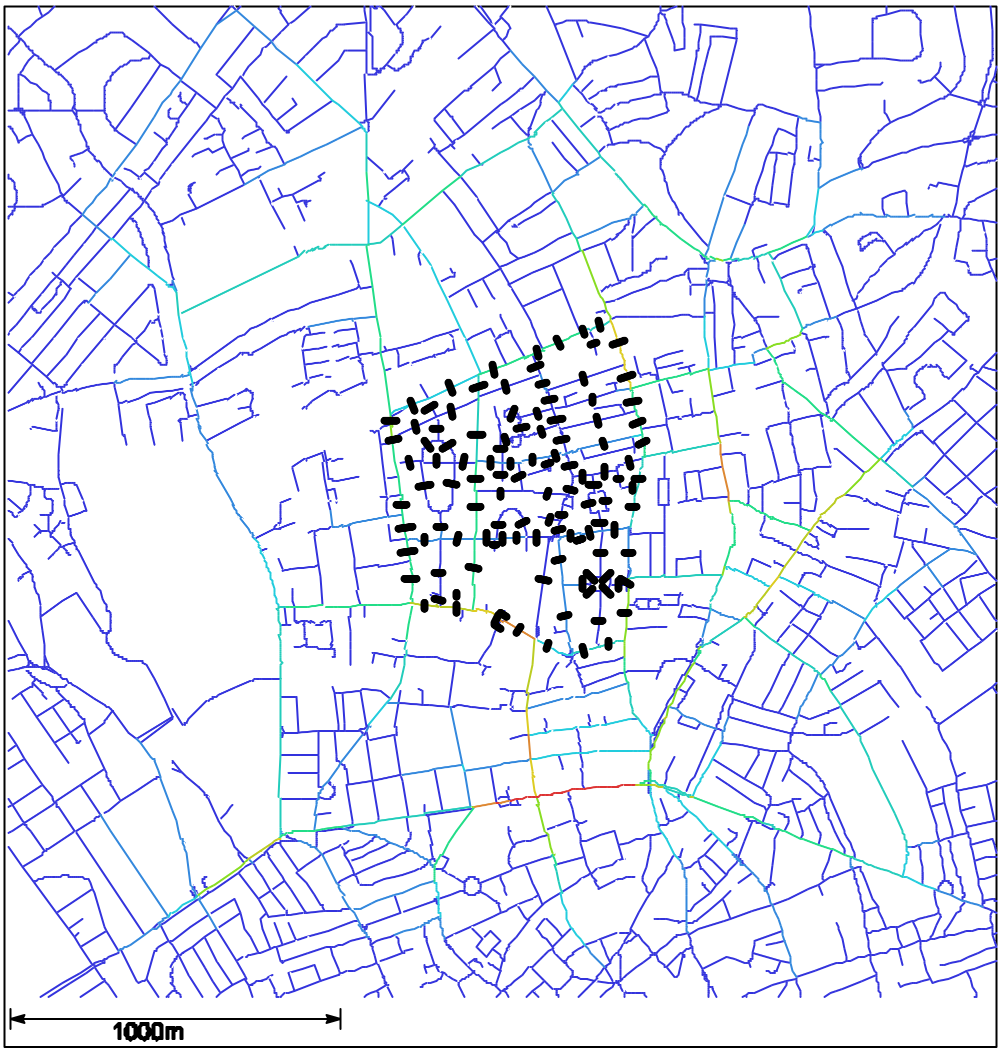

Figure 4. The analysis area of Barnsbury, North London. The thick black marks show the gates observation locations, while the road-center lines are colored according to their weighted betweenness values (B_w), for journeys up to 2000m long. Blue lines have low B_w, through green to red for high B_w. The red line picked out near the bottom of the frame is a section of the London inner ring road. Road-center lines reproduced from Ordnance Survey data © Crown Copyright.

For the experiments we varied the radius parameter between 500m and 5000m, and examined the correlation between average daily vehicular flow and betweenness values (B_w) at each of the observed 112 gates, using shortest path based on each of the minimum angular path and the minimum block- or Manhattan-distance paths. In order to calculate a correlation coefficient, the data values of both the gate observations and the B_w values were first converted to a near-normal distribution by taking the cube root (chosen as a simple function to apply), and then rescaled to the range 0 to 1 (with 0 at the original 0 for model and observation consistency). Obviously a model constructed like this falls well short of the requirements of standard traffic analysis: it fails to account for the diurnal ebb and flow of commuter traffic, and does it not include driver response to congestion or any other variable. Furthermore, it only assesses *relative* rather than absolute flows. However, it does allow us to plot the difference between the angular shortest path assumption and the block or Manhattan-distance shortest path assumption, as shown in figure 5.

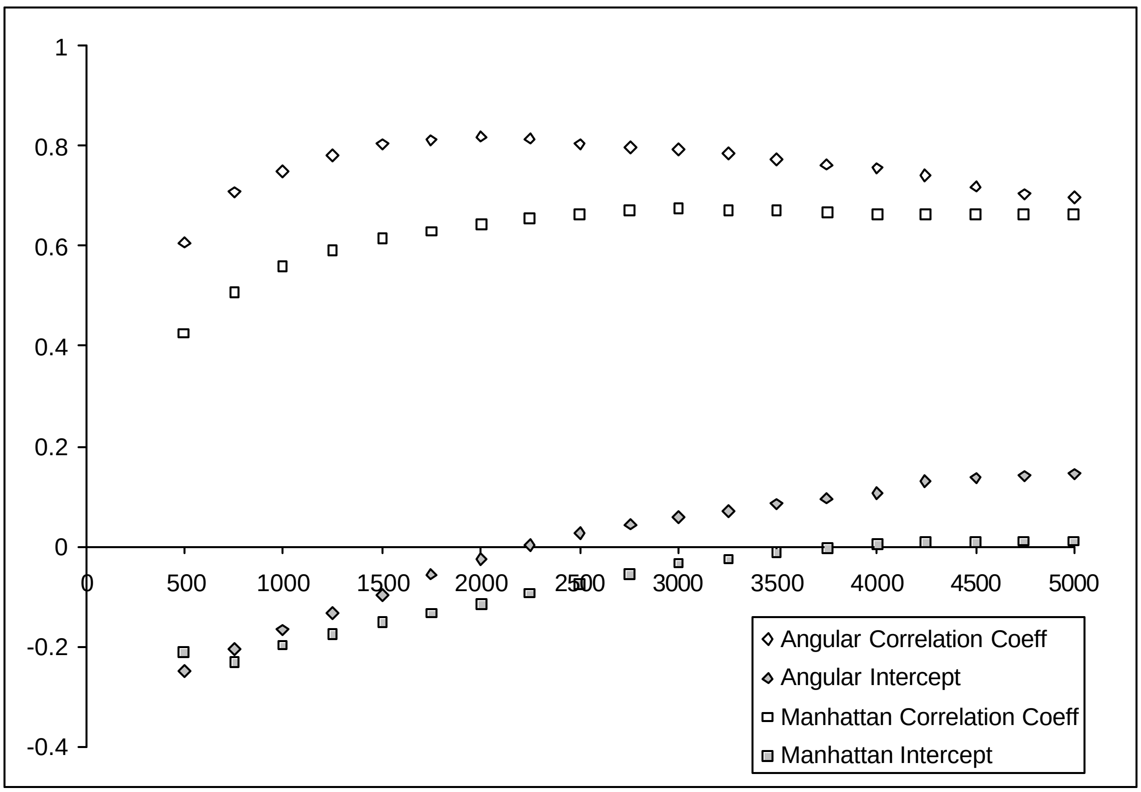

Figure 5. R^2 correlation coefficient for angular and Manhattan-distance path assumptions, with associated intercept in normalized units, as the path-length radius is varied.

For the angular model, the correlation coefficient, peaks at $R^2 = 0.82$, at a radius of 2000m (i.e., all segment to segment journeys up to 2000m long are considered); for the block-distance model, the correlation peaks at $R^2 = 0.67$ at radius 3000m. In both cases, the peak correlation is found approximately where the intercept of the regression line passes through the origin. That is, where the model is strictly proportional between traffic flow counts and B_w values. We can investigate the effect of radius change in more detail by looking at scatterplots of the results. Figure 6 shows how the distribution of traffic count to B_w point values changes as the radius is varied for the angular model. It can be seen that at radius 1000m, the model under-compensates for through-journeys, so short range journeys correlate reasonable well, but the higher flow roads have too few journeys modeled, resulting in an L-shaped graph. At 2000m, the balance is about right, and there is approaching linear correlation. At 5000m, the situation becomes less clear, and the data appears to split in two: edge effect is now taking place, so that nodes that lie nearer to the edge have under-predicted flow, while more centrally located nodes are less affected.

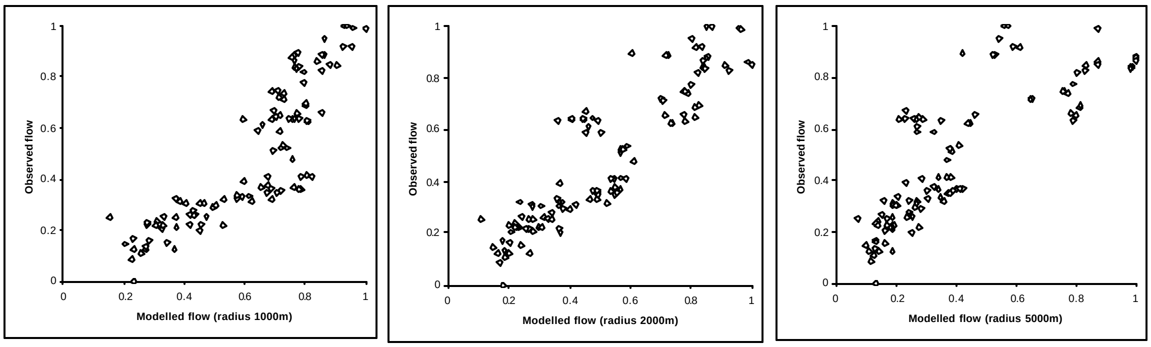

Figure 6. Scatterplots of observed traffic flow against modeled traffic flow at radius 1000m, 2000m and 5000m for minimum angular path model.

Figure 7. Left: Weighted betweenness (B_w) values for the minimum angular model at radius 2000m. Right: B_w values for the minimum block-distance model at radius 3000m

We can also look in more detail at the difference between the patterns of B_w in the street network according to the angular model and the block-distance model. Figure shows a close-up of the central analysis zone for the two models, at radius 2000m and radius 3000m respectively (the best correlating model in each case). Note how the shortest block-distance model picks up what we might identify as commuter 'rat-runs': shortest path routes using side streets. In fact, the council planners have tried to prevent rat-runs through the use of one way streets and blocking the end of roads. Although we modeled the blocked ends of streets, the one-way streets are not modeled, and it remains to be seen if either of the correlation coefficients would be improved upon further by the addition of this detail[4].

5. Implementational Details

5.1 Algorithm

All the experiments in this paper were conducted using UCL's Depthmap 5.0r software[5], which was extended by Turner especially for the purpose of testing the ASA algorithm. The software is implemented in C++. The network is first loaded as a series of line segments, and the junction points identified. These are linked into a graph as described in the methodology section, with each segment being assigned a set of 'forward' and 'back' links. In order to calculate the betweenness, the shortest paths are first calculated using a breadth first search on a node by node basis: the first node is started using both 'forward' and 'back' links, but after this the directionality is maintained, so a node entered via a 'back' link must be left via a 'forward' link and vice versa. As each shortest path is discovered, we chain back through the nodes to calculate the betweenness (B_w) value. As this chain could be up to N nodes in length, technically it brings the algorithm to $o(N^3)$. However, chains in these networks are relatively short, as a street network, even in the UK, is roughly arranged as a grid. The maximum chain length in a square regular lattice is from one corner to the far corner, comprising vN nodes (along-up-along-up, or any other permutation), and although the road-center line network has many inter-junction segments in, for example, a curving street, the angular and block-distance path cost of these inter-junction segments can be pre-calculated (which has the beneficial side effect of reducing N in the breadth-first search). In all, then, we have an algorithm that works in about $o(N^{2.5})$ time. Although processing on a node by node is less time efficient than constructing an N by N matrix for all nodes and constructing the shortest paths simultaneously, the memory efficiency is considerably reduced. Nevertheless, for a true angular analysis, the cost is still prohibitively slow. However, we can work on the principle that the computer must digitize the angular cost at some fine resolution in any case, so why not discretize more coarsely? We therefore create 512 angular 'bins' to perform the search, where bin 0 represents straight ahead (0º turn), and bin 511 represents the maximum increase in angle at any one step (a 180º). Now the search can loop through, putting each discovered node in the appropriate bin, up to 511 bins ahead of the current node. Thus, if we loop around when adding to the bins, we can simply perform the search by checking the contents of a fixed set of 512 bins at each stage. The search algorithm in pseudo code is as follows:

```
add current search node to bin 0
set current search bin to 0
add all nodes to unchecked list
while unchecked list has nodes loop
  while current search bin is empty loop
    increment current search bin
    if current search bin is 512 then set current search bin to 0
  end loop
```

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[4] One-way streets are easily added to the model simply by disconnecting the links to its forward direction from the set of connected segments, while maintaining its links to them.

[5] For more details about Depthmap see http://www.vr.ucl.ac.uk/depthmap/

```
  select a random node, X, from the current search bin
  if X is in unchecked list then
    remove X from unchecked list
    remove X from current bin
    for all nodes, Y, connected to X in direction of travel loop
      set next bin to (current bin plus Y’s connection weight) modulus 512
      add Y to next bin
      set Y’s path recovery pointer to X
    end loop
  end if
end loop
```

Note that, in most cases, each bin will have only one member node at any one time. However, in rare cases, there will be two (or more) routes with exactly the same path length. In this case we choose one or other node at random, as shown in the pseudocode. This has a side effect that in the extremely rare case where there are two identical shortest paths, one or other will be chosen at random. Of course, given that there are many nodes in the system, in general the paths will distribute their weight evenly. This algorithm also leads to an interesting question for further research: if we reduced the number of bins to just four (for example), would we approximate Sadalla and Magal’s (1980) ‘number of turns’ cognitive distance? Unfortunately, the initial answer is no, as some segments combine together in a curve to make to make 90º, whilst others meander back and forth, without really adding a cognitive step, although the total angle may again sum to 90º. Unfortunately, the algorithm cannot distinguish between these two cases as it stands, and would simply use bin 0 if the angle between any individual pair of segments were less than the bin resolution angle.

5.2 Performance

It is of course always difficult to compare performance with so many different hardware combinations. The experiments in this paper were run on a single processor PC with an AMD Sempron 2400+ chip and 512MB of SDRAM. The 3km × 3km analysis area comprised 20,874 individual road-center line segments. With the algorithm as it is, the lower radii are obviously significantly faster to analyze than the higher radii. In the latest version of Depthmap, we have added a feature to run all the radii simultaneously, however, for this paper each one was run individually. For radius 500m, the system took about 3 minutes to analyze; for radius 5000m, the system took about 24 minutes to analyze (this hits the edges of the 3km × 3km, but rember the radii are block-distances not as-the-crow-flies distances). As stated, the algorithm scales at approximately $o(N^{2.5})$, so we would expect that a 100km^2 area would take in the region of 150 hours to process, based on 9km^2 in 24 minutes, with N scaling linearly with area. We also have to consider memory efficiency of the process, which scales with $o(N)$. The Depthmap process currently occupies 66MB when analyzing the Barnsbury area, so for a 100 km^2 we would expect the process to fit easily within 1GB memory.

6. Conclusion

In this paper, we have proposed a simplified route choice model of vehicular movement using the assumption that drivers take the shortest angular path between origin and destination. We argued that while conventional analysis focuses on how people perceive utility of various physical factors of the environment, we should focus on what their underlying cognitive model of space is. We appealed to Sadalla and Magal’s (1980) segmentation theory of cognitive distance, where the length of a trip is adduced from the number of turns during the journey rather than the energy expended, to suggest that drivers might try to minimize the total angle turned on a route between origin and destination.

Our model is constructed from standard topological road network data (for example, TIGER line data in the USA, or Ordnance Survey road-center lines in the UK; for the purposes of validation of our model, we showed an example using OS road-center lines). Rather than making a simplification of the network, we simply convert the road-center lines directly into a graph, and, in a further modification to standard models, each straight-line segment within it is treated as a node rather than an edge. The edges are therefore the junctions between the segments, and the edge-weight from one segment to another is formed by the angular turn from the current segment to the next. Rather than employ a sophisticated route allocation model, such as logit or probit, we simply assume that drivers will always take the shortest angular path between origin and destination. The origin and destination model is also simplified, so that every segment is treated as an origin, and also as a destination. These simplifications allowed us to use the simple graph measure of betweenness (Freeman, 1977) to act as an approximation of vehicular flow through segments (although the measure of betweenness must be weighted by the length of the origin and destination segments, so that the total number of journeys remain constant no matter how the cartographer splits segments between junctions).

In order to validate our model, we took the data from a similar previous study by Penn and Dalton (1994), and compared 112 'gate' observations of passing vehicle counts to values of weighted betweenness obtained using the shortest angular path criterion. As a control experiment, we also repeated the analysis with the assumption that drivers would take minimum shortest distance paths. We found that the shortest angular path model strongly correlates with traffic movement. The correlation coefficient peaked at about $R^2 = 0.82$ when a parameter of maximum trip length was set in to 2km. These results significantly improve on those found with a minimum block-distance assumption, which lead to a peak correlation coefficient of around $R^2 = 0.67$ with a maximum trip length of 3km.

Although these findings are extremely encouraging for the shortest angular path assumption, we still need to verify the model works on other systems. In addition, we have simply compared relative flows: we need further experiments to discover if there exists a proportionality constant that holds across different systems, or if there is an effect when significant quantities of traffic originates from further away. There is also the unresolved question of whether the correlation arises due to the perception of the choices presented to the driver during the journey, or if it is instead a function of trip planning further ahead. Regardless, the high correlation coefficient implies that angular variation between routes does indeed affect the usage of a road-network. Furthermore, since the theory of angularity is imported from observation of pedestrian participants, it seems reasonable to hypothesize that the method may well also be applicable to the analysis of pedestrian as well as bicycle networks.

7. Acknowledgements

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8. References

Bell, M. G. H. and Iida, Y., 1997. *Transportation Network Analysis* (John Wiley and Sons: Chichester).

Ben-Akiva, M. and Bierlaire, M., 2003, Discrete choice models with applications to departure time and route choice, In *Handbook of Transportation Science, 2nd edition* (Kluwer Academic Publishers) pp. 7–38.

Ben-Akiva, M. E., Cyna, M. and de Palma, A., 1984, Dynamic model of peak period congestion. *Transportation Research B*, **18**, 339–355.

Cascetta E., Russo F., Viola F. A. and Vitetta A., 2002, A model of route perception in urban road networks. *Transportation Research Part B – Methodo1ogical*, **37**, 577–592.

Conroy Dalton, R., 2003. The Secret Is To Follow Your Nose: Route Path Selection and Angularity. *Environment and Behavior*, **35**, 107–131.

Dalton, N., 2001, Fractional configurational analysis and a solution to the Manhattan problem, In *Proceedings of the 3rd International Symposium on Space Syntax* (Georgia Institute of Technology: Atlanta) pp. 26.1–26.13.

Duckham, M. and Worboys, M., 2001, Computational structure in three-valued nearness relations, In *COSIT 2001, Lecture Notes in Computer Science Vol. 2205*, 76–91.

Duckham, M. and Kulik, L., 2003, "Simplest" Paths: Automated Route Selection for Navigation. In *COSIT 2003, Lecture Notes in Computer Science Vol. 2825*, 169–185.

Freeman, L. C.,1977, A set of measures of centrality based on betweenness. *Sociometry* **40**, 35–41.

Hillier, B. and Hanson, J., 1984. *The Social Logic of Space* (Cambridge University Press: Cambridge)

Hirtle, S. C. and Gärling, T., 1992, Heuristic rules for sequential spatial decisions, *Geoforum*, **23**, 227–238.

Hochmair, H., Frank, A. U., 2002, Influence of estimation errors on wayfinding decisions in unknown street networks analyzing the least-angle strategy, *Spatial Cognition and Computation*, **2**, 283–313

Jan, O., Horowitz, A. J. and Peng, Z.-R., 2000, Using GPS data to understand variations in path choice, *Transportation Research Record Vol. 1725*, 37–44

Montello, D. R., 1991a, The measurement of cognitive distance: methods and construct validity. *Journal of Environmental Psychology*, **11**, 101–122.

Montello, D. R., 1991b. Spatial orientation and the angularity of urban routes: a field study. *Environment and Behavior*, **23**, 47–69.

Nakayama S., Kitamura R. and Fujii S., 2001, Drivers' route choice rules and network behavior – do drivers become rational and homogeneous through learning? *Transportation Research Record Vol. 1752*, 62–68.

Sadalla, E. K. and Magel, S. G., 1980, The perception of traversed distance. *Environment and Behavior*, **12**, 65–79.

Sadalla, E. K., Burroughs, W. J., and Staplin, L. J., 1980, Reference points in spatial cognition. *Journal of Experimental Psychology*, **6**, 516–528.

Penn, A. and Dalton, N., 1994, The architecture of society: stochastic simulation of urban movement. In *Simulating Societies: The Computer Simulation of Social Phenomena*, (UCL Press: London) pp. 85–125.

Tversky, A., 1972, Elimination by aspects: a theory of choice, *Psychological Review*, **79**, 281–299.

Tversky, B., 1992, Distortions in cognitive maps, *Geoforum* **23**, 131–138.

Turner, A., 2001, Angular analysis, In *Proceedings of the 3rd International Symposium on Space Syntax* (Georgia Institute of Technology: Atlanta) pp. 30.1–30.11.