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ABSTRACT

This paper presents a new method for forecasting cyclist volume and route choice based on space syntax techniques for urban analysis. Space syntax has been shown to correlate strongly with pedestrian and vehicular trips in a number of international studies, but little research to date has focused on the role of urban form and street network design in cyclist route choice. This paper addresses this gap by analyzing the distribution of cycling trips in the central London area, focusing on a sample of work-based commuting trips. A sample of 423 cyclists from 50 organizations was combined with cordon volume counts at several Central London locations. It was found that individual cycle trips were subject to a wide range of variables that made individual traces difficult to predict, but that total cyclist volumes corresponded strongly with the most accessible, direct streets in the urban network. This research suggests that angular minimization is an important factor in cyclist route choice and that measurement of least angle routes in urban environments can be a useful way of predicting cyclist volumes and route choice. Such techniques have the potential to save planners and policymakers the expense of performing origin destination studies and may offer a useful tool for cyclist volume prediction.

1.0 INTRODUCTION

Non-motorised transportation has become an important part of the international urban sustainability agenda. In the United Kingdom, the Office of the Deputy Prime Minister (ODPM) and the Department for Transport (DfT) aim to “promote more sustainable transport choices” and “accessibility to jobs, shopping, leisure, facilities and services” through public transport, walking, and cycling (1,2). In the United States, similar efforts have been introduced, with the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) and the Transportation Equity Act of the 21st Century (TEA-21) provide funding and guidance to support the construction of cycling infrastructure and education programs across America.

Despite the importance of cycling in million of people’s daily lives, little research has been published on the urban design factors affecting cyclists; none of it using space syntax research methodologies. What research does exist has tended to focus on mode choice (or why people choose cycling over other modes of transport) or cycling infrastructure design issues (cycle lanes, parking facilities at the destination, etc.) (3, 4, 5). Early work by Ashley and Banister (6) used UK census data to evaluate the factors influencing cycling to work and developed a model using personal characteristics, trip distance, availability of cycling facilities, car ownership, and local climate. Nelson and Allen (7) also analyzed 18 U.S. cities to predict work trip cycle mode split from census data which was based on weather, terrain, the number of college students, and the per capita miles of bikeway facilities. They found that the presence of good bikeway facilities contributed to higher percentages of cycle trips to work. Finally, Ridgeway (8) developed a regression model based on census data and travel time that worked well in most cases.

This research may provide guidance on the type and percentage of people cycling, but has little to say about the strategies that cyclists use to determine their route choice once on their bicycle. In particular, no rigorous analysis of the influence of urban design or transport network factors has been conducted to date (9). Noël and Lee-Gosselin (10) used surveys to build trip diaries in Quebec City, Canada, but did not analyze the relationship between stated preference and actual route choice. Abraham et al (11) conducted a stated preference survey asking cyclists in Edmonton, Canada to choose between two hypothetical route options to an “all day meeting”. Their survey found that cyclists preferred routes with designated cycling facilities and ones which offered destination-based services such as the availability of parking and showers at the destination. Forester (12) and Wilkinson et al (13) reported that perceived safety was an important issue for cyclists when making route choices, as well. Although factors influence cycling mode choice are relatively clear, route choice remains an important and poorly understood problem.

The current paper uses space syntax techniques to analyze the relationship between street accessibility and cyclist route choice. It was hypothesized that cyclists balance their total journey length and route directness to achieve the fastest and easiest transit between origins and destinations. A secondary hypothesis was that cyclists balance route choice heuristics with other safety issues such as the presence of dedicated cycling lanes.

Three datasets from Central and South London were used to test this hypothesis using space syntax spatial accessibility analysis and multiple regression statistical modelling. It was found that individual variability in cyclist route choice, as based on a revealed preference sample of 423 self-reported routes from work-related cyclists, was too great to yield predictive utility. Subsequent analysis of two separate gate count data sets revealed, however, that cyclist route choice was strongly correlated with mean angular minimization, combined with the presence of cycling lanes (r-squared of 0.67 in Stockwell and of 0.76 in Elephant and Castle). Both results were found to be statistically significant (p value < 0.0001) and suggest that although individual cyclist choices may be effected by a wide range

of variables, system level cyclist route choice follows an emergent logic based on route directness.

This study differs from previous research on cyclist behavior for two reasons. Unlike location case studies (22, 23) which aggregate cyclist data based on large geographic zones and therefore lose specific explanatory power, the current approach retains block by block accuracy across a large geographic area. It also differs from polls of cyclists or validated expert opinion (5), which are highly biased by response rates, perceptions of the cycling environment, and survey design (9). This study's efforts to analyze self-reported cyclist traces place it within the tradition of revealed preference studies but it differs from past studies through the use of comparative route choice algorithms combined with actual data (24). Finally, unlike any past studies of which the authors are aware, this research combines the use of actual cyclist volume counts with revealed preferences, a combination which Hunt and Abraham call "an excellent way to establish parameters of choice models" in their review of cyclist research methodology (9).

This combination of an innovative spatial modelling approach and a rare cyclist data set suggests that the current research may be useful for the sustainable transportation research community at large, as well as those more focused on the advances in urban transportation modelling.

2.0 METHODOLOGY

The role of spatial accessibility in pedestrian movement has been well documented (14, 15). Traditional space syntax graph representation of the transport network relies upon the axial line as the main form of spatial measurement. Recent innovations by Turner (16,17), Dalton (18) and Hillier and Iida (19) have found street segment level angular analysis to correlate better with pedestrian movement in many cases. This study used both traditional space syntax axial modelling techniques and new angular segment based modelling techniques to explore the effects of transport network layout on cyclist movement.

2.1 Space Syntax Accessibility Measurement

Space syntax is a suite of techniques used for measuring the effects of urban form and street network design on accessibility and movement. The approach has been widely tested internationally but has only recently come to the attention of mainstream researchers within the United States.

The technical background of space syntax has been well explained in more detail elsewhere (16, 17, 18, 19). Nonetheless a brief introduction may be useful for those unfamiliar with its techniques. Space syntax models analyze urban street networks through the use of road centerline-like measurements called 'axial lines'. These lines are used as mathematical representations of the "least line set" of all public open spaces within a city. Traditionally this differs from strict road centerline measurement because pedestrians are influenced by centerline restrictions than vehicles and are therefore more able to make full use of the urban spatial networks represented by the open space between buildings. These lines are then analyzed using topological analysis as a measure of accessibility and have been found to correlate strongly with urban pedestrian movement in a wide variety of European, Asian, and American cities.

Traditional space syntax models considered a single axial line as unit of measurement. Such a line may often stretch over a long distance, with a single straight line crossing

multiple streets and intersections. This has been criticized as failing to take into account the effects of distance on long straight streets and introducing too artificial segmentation on curving streets.

A new form of space syntax analysis, known as angular segment analysis (ASA), was developed to address these concerns. Angular segment analysis breaks each axial line down into its individual street segments and analyzes them for their angular difference between them. This allows for a higher resolution of analysis can be conducted on a street by street, junction by junction basis, and a more subtle measurement of topological depth along curving streets (17). Instead of the axial line as a whole, each street segment is treated as a separate node of a graph and is assigned a fractional depth value to each line based on the angle of intersection that it meets with its neighboring lines. Thus two segments which only vary slightly in angle will be given a smaller depth change value than those which vary more substantially. The extent of topological depth change usually varies between 0 (where segments meet end to end with no angular change) and 1 (which represents a 90 degree change of direction). In this way angular segment analysis may offer a more realistic model of the urban environment that can take into account more subtle measures of configurational change. Indeed, recent results seem to indicate that the mean angular depth measure of angular segment analysis correlates substantially better than traditional axial topological analysis in some cases (19).

To evaluate which spatial model related best to cyclist route choice, both traditional axial analysis and angular segment analysis were constructed for the purposes of this study. A traditional axial map was constructed which covered an area of approximately 120 km² in Central London, both north and south of the River Thames. This model was composed of approximately 12,000 axial lines. A second, segment based spatial model was then created based upon this axial map using the UCL software program Depthmap (21). This produced a suitable segment model which covered the same area, but was composed of nearly 47,000 segments.

Figure 1 displays the larger context of the segment model, while **Figures 2** and **3** provide close-up pictures of the segment maps of Stockwell and Elephant and Castle areas respectively. These maps are colored thematically, with thicker, darker lines representing segments with lower mean angular depth. This means that these segments require less average change of direction then other segments to reach all other segments in the system.



FIGURE 1 Study areas in context, angular segment model.



FIGURE 2 Angular segment map of Stockwell study area.

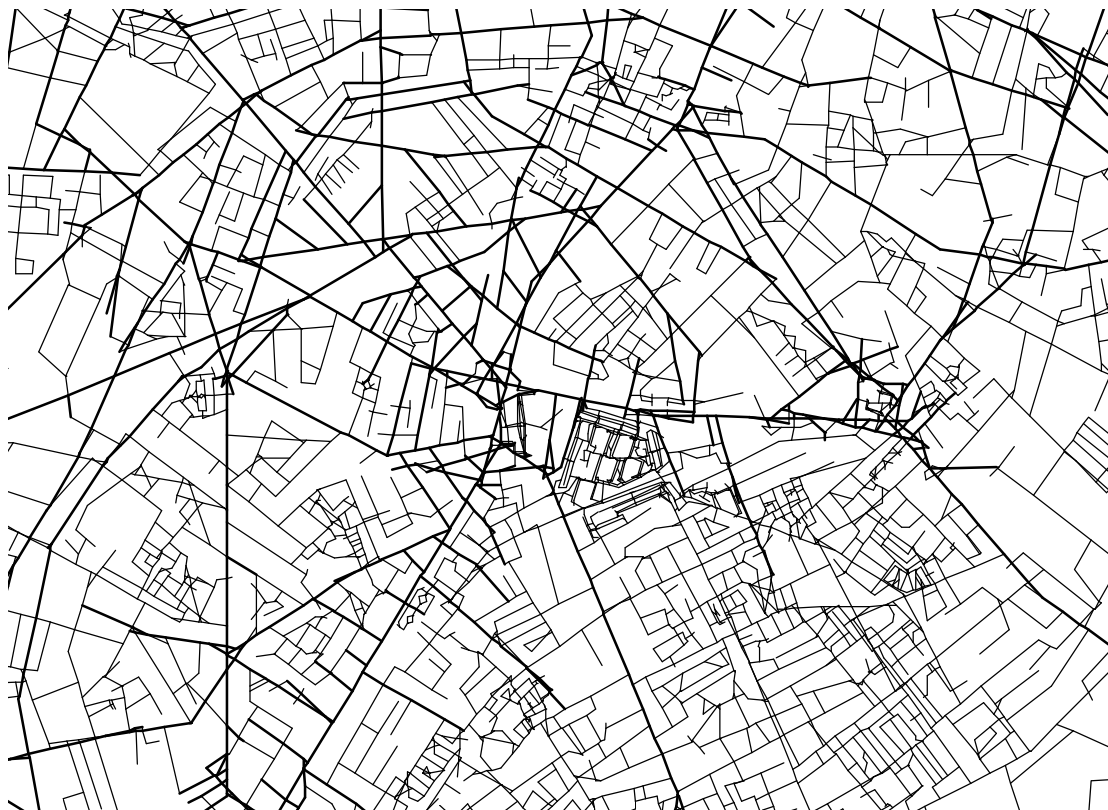


Figure 3 Angular segment map of Elephant and Castle study area.

2.2 Cyclist Data Sets

Cyclist data was then collected from three separate sources was analyzed in two phases. First, a data set of 423 separate cyclist traces connecting an equal number of origins and destinations was utilized. This data was gathered as part of the “Business Cycle” project conducted by the Space Syntax Laboratory for the Central London Partnership, in which traces of cyclist routes were gathered from employees of nearly 50 government and private agencies located in Central London. Employees were given maps of the study area and asked to draw their cycle routes to and from work, resulting in a total sample size of 423 traces (approximately 45% response rate from each organization). These traces were then entered into the GIS database for coding and analysis. **Figure 4** displays the overlay of cyclist traces in the Central London area.

The second phase of the study used gate counts of cyclist volume from the Stockwell and the Elephant and Castle areas of London. The Stockwell data set included 46 separate observation gates collected between 12:00 PM and 20:00 PM during weekday and weekend periods. The Elephant and Castle data set included 64 separate observation gates collected over a twelve hour period between 8:00 AM and 20:00 PM on both weekday and weekends. These gates counts were cleaned to exclude gates on cul-de-sacs, gates in housing estates, and gates with no observed cyclists. Analysis was also only conducted on weekday counts during this study, but the presence of weekend cyclist volumes offers the potential for future research which could capture leisure and non-work based trips with more detail.



FIGURE 4 Cyclist movement traces.

2.3 Route Choice

These data sets were analyzed in two phases. A first approach attempted to utilize the axial lines and segments which contained cyclist traces as gates themselves, thus conducting a simple regression analysis between spatial variables and the number of traces per segment. This produced no meaningful results, requiring an alternative approach to be carried out. A random 10% sample of all traces was then selected ($n = 46$) and each trace analyzed from its origin to its destination to determine if the trace followed the shortest route (as measured by metric distance) or the fastest route (as measured by a combination of most integrated and shortest metric distance routes).

Each cyclist trace was then analyzed to determine the percentage of the actual route which intersected an ideal shortest route or an ideal “fastest cognitive route”. This new term refers to how people may map their trajectory within an environment, with emphasis on spatial relationships as opposed to strict metric distance, and is a combination of mean angular depth and metric distance values. A GIS-based shortest path algorithm was utilized to calculate the shortest distance from each trace’s origin and destination point, and was then weighted using mean angular depth values to determine the “fastest cognitive route” by using a combination of angular integration and metric distance values. The percent of each cyclist trace which fell one or both of these routes was then calculated. **Figure 5** displays an example of a cyclist trace compared to its shortest metric distance route and fastest cognitive route.

It was hypothesized that if a cyclist preferred one route choice logic to another (shortest vs. “fastest, or most integrated”), then the majority their trace would overlap the ideal route of one logic or other. Therefore the relative percentage of the total trace which intersected an ideal shortest or most integrated path was expected to reveal their preference.

The second phase of analysis involved more standard space syntax analytical techniques; statically regressing gate counts against spatial measures. Cyclist volumes from two separate date sets in Stockwell and Elephant and Castle in south London were utilized for this purpose. Multi-radius axial integration, mean angular depth, supergrid values, line length, segment length, and connectivity were all compared against logged and unlogged observed counts. Additional non-spatial factors were also considered, including the presence or absence of cycling lanes. All variables were put into a multiple regression model and analyzed for covariance. The findings of both these approaches are presented below.



FIGURE 5 Example of shortest path vs. “fastest cognitive route” overlay analysis

3.0 FINDINGS

The study was divided into two phases; analysis of cyclist route choice and correlation with cyclist gate counts. The findings of these analyzes are described below.

3.1 Individual Cyclist Routes

The first phase of analysis examined the correspondence between actual cyclist traces and the shortest metric path versus the fastest, “shallowest” angular path between origin destination pairs. For example, if 60% of a trace’s total length corresponded to the ideal shortest metric path, it could be said that this trace followed a shortest path distance heuristics. If 60% of the trace followed the fastest cognitive route (i.e., the “shallowest” path), then it could be said to be minimizing angular change. Neither of these extremes was actually found in the data, however, suggesting more complicated factors at work at the level of individual cyclist paths.

In 86% of the cases ($n = 35$), the shortest and fastest paths were very similar and displayed r -squared of 0.90 between shortest and fastest cognitive route lengths. This demonstrates little overall difference between shortest metric and most integrated routes in most cases; a finding which supports earlier theoretical work by Hillier (25) which found that there is often a choice between three or four “reasonable” routes from a given origin-destination pair. Distance is often minimized to within 5% between such alternatives, suggesting that pedestrians will chose the simplest route in terms of the least change of direction if given a preference. Moreover, Hillier writes that “as the crow flies shortest paths [are] usually approximated in terms of distance by at least one of the syntactically simpler routes” (Hillier, 1986).

Of the 46 cases examined it was found that 21 (~45%) displayed predominantly shortest metric path preference, while an equal number ($n = 21$, or ~45% displayed

predominately fastest cognitive route preference. This suggests that neither shortest path nor most integrate path logics were dominant for the individual traces selected in this sample. That these results are so close to a 50 / 50 percentage split suggests that any given route choice criteria may have equal probability of selection by an individual cyclist and is likely to be heavily influenced by other factors.

More importantly, these findings are supported by additional evidence which found that the mean length of traces falling along one of these ideal paths was only 46%. Greater than 54% of all cyclist trace lengths fell off an ideal shortest or fastest route, providing further evidence that alternative logics or unpredictable elements such as scenic preference, personal fitness / demographics, or other factors not included in this model may strongly influence individual cyclist route choice. Qualitative analysis of the sample traces did find that many traces paralleled ideal routes, or chose routes which may be combination of several potentially shortest / most integrated routes. This suggests that cyclists may choose between one of a series alternative routes, all of which may approximate the most integrated or shortest path but do not fall exactly on the shortest or most integrated lines (25).

3.2 Aggregate Cyclist Volume

The second phase of this study compared actual cyclist gate counts with spatial variables using a multiple regression model. Contrary to the findings of the first phase, it was found that cyclist volume correlated strongly with the configurational variable mean angular depth in both Stockwell and Elephant and Castle. When combined with segment length and a dummy variable recording the presence of cycling lanes, global mean angular depth correlated to cyclist counts with an r-squared value of 0.76, with a p value of less than 0.0001. In Stockwell, global angular mean depth was found to correlate with a slightly lower r-squared value of 0.68, also with a statistically significant p value of less than 0.001. Segment length was not found to be a significant factor in cyclist route choice in Stockwell, nor was the presence of cycling lanes.

Figure 6 displays the scatter plots and the statistical output of the multiple regression models. In both cases it can be seen that global mean angular depth correlated powerfully with observed cyclist volumes. This demonstrates that streets which feature low overall angular change receive more use, and that there is a relationship between mean angular depth and system level cycling activity.

Although individual cyclists may not prefer least angular change routes, system level cyclist volume clearly favors such routes. This appears to contradict the findings of the individual cyclist traces. The following section discusses this condition and attempts to offer a reconciliation if this apparent paradox.

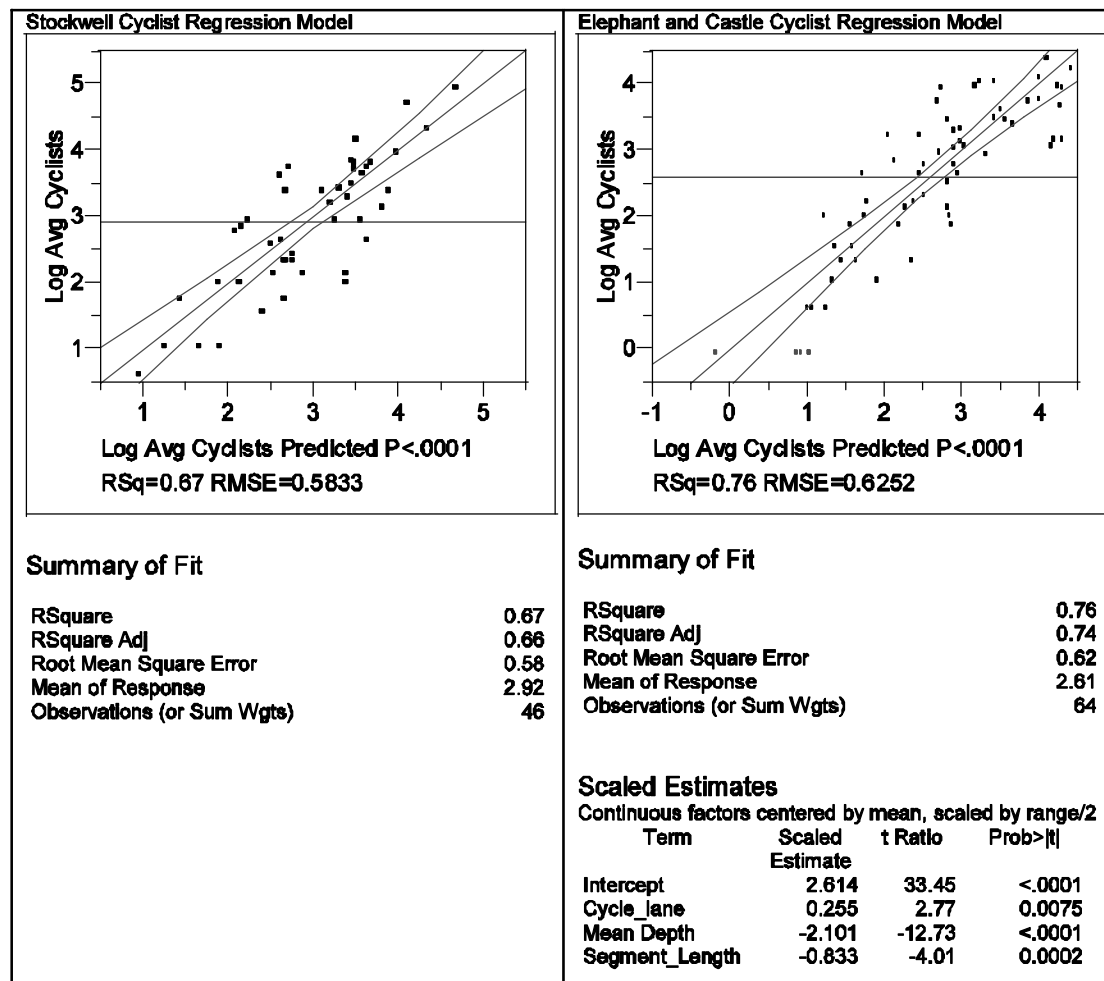


FIGURE 6 Cyclist MRA regression models: Stockwell and Elephant and Castle.

4.0 DISCUSSION

The findings of this study appear contradictory upon first glance. The analysis of cyclist traces from 50 organizations located in Central London approximated an equal probability distribution between route choice strategies, with less than half of all traces falling along an “ideal” shortest path or “fastest cognitive route” paths. Of those which did fall on such a path, there was a near even split between shortest versus most integrated route choice, further confusing the matter. The multiple regression model of the cyclist gate counts in Stockwell and Elephant and Castle, however, found strong and statistically significant relationships between mean angular depth and aggregate cyclist volume, apparently contradicting the individual cyclist traces. How can this paradox be logically reconciled?

It is suggested that like pedestrian and vehicular movement, cyclist movement exhibits emergent properties characteristic of complex dynamic systems. At the individual level, any number of factors may influence a given cyclists’ choice of route. These variables could range from things as concrete as avoidance of high traffic streets or use of parallel routes, to more abstract environmental variables such as aesthetic preference. This individual variation can be seen in the analysis of the cyclist traces, which conformed to neither shortest path, most integrated path, or any similar logic.

When many cyclist journeys are aggregated independent of origin and destination, however, the sum of all of interacting route choices appears to conform to a powerful spatial

logic. The fact that the majority of cyclists counted at the gates in south London varied with mean angular depth indicates that at the system level, total cycle volume is strongly influenced by configurational variables. So called “through-movement”, as opposed to destination specific “to movement”, thus appears to be particularly well represented by angular depth measurements.

This makes sense when considered from a global systems perspective. Although an individual cyclist’s route might not minimize their angular change along all legs of their journey, streets with lower angular mean depth will experience higher volumes of cyclist traffic because they are probabilistically “shallower” to more origin – destination pairs. The cumulative effect of many cyclist trips between many origins destinations is therefore more likely to follow least angular change routes, even though individual cycle trips may not. It appears that the principle of natural movement, as described by Hillier et al. operates consistently with cyclist movement as well as pedestrian and vehicular movements (14).

The presence of cycling lanes in the Elephant and Castle dataset also slightly improved correlation with observed cyclist volumes. The cyclist friendly infrastructure clearly plays some role in cyclist route choice as well; a finding is confirmed more powerfully in other studies (van der Waerden et al., 2003). Of these all factors however, it is clear that mean angular depth is the most powerful factor explaining variation in cyclist volume at the system level. The mean angular depth variable displayed a t Ratio of -12.73 in the multiple regression analysis, while the presence of cycling lanes only displayed a t Ratio of 2.77. This means that the mean angular depth variable explained nearly five times the variation in cyclist volume than the presence of cycling lanes. No other variables were found to be as important.

This is the first time that the “natural movement” phenomena has been found for cyclists, suggesting that space syntax may have further advantages for research within the cyclist research community. These findings are also particularly important in light of existing transport planning, which has suggested that metric trip length not to be an important or significant variable (26, 27). It may be that although geographic trip length is an important variable, angular minimization may be of equal or greater importance. This suggests an entirely new approach for researchers interested in cycling route choice and route planning, one which could have significant benefits for the urban planning and transport engineering communities (28).

5.0 CONCLUSIONS

This paper found that angular minimization is an important factor in overall cyclist volumes and may be a useful tool for cyclist volume prediction. On the individual level a wide variety of alternative factors appeared to influence route choice. At the aggregate level, however, angular minimization emerged as the dominant explanatory variable, correlating to nearly 70% of observed cyclist volume.

This suggests that angular segment analysis is able to capture an essential aspect of perception and decision making at the system level which does not appear in individual cyclist route choices. It may therefore be an important factor in predicting cyclist route choice and volume, as demonstrated in this example.

5.1 Cyclist Preference and Route Choice Econometrics

Origin-destination estimation and route choice preference are important components of traffic models which provide policy guidance for a wide variety of urban applications such as traffic control, route guidance, incident management, planning, and construction mitigation. O-D

flows are also essential input to the traffic assignment phase of most four-step based traffic models.

Many such techniques rely upon stated and revealed preference studies to construct the discrete choice frameworks upon which these models depend (28). A credible preference analysis must employ a survey that produces an accurate ordering of preferences and must use an appropriate econometric technique to obtain consistent and efficient parameter estimates. This paper shows that at the individual level, these parameters may be compounded and could lead researchers to misleading conclusions if they analyze individual route choice preferences alone.

It is therefore argued that it is necessary to analyze cyclist behavior at the system level, independent of individual O-D studies, in order to build an accurate picture of cyclist movement in urban systems. This study has shown that angular analysis is a tractable topological and geometrical variable which can be used to measure the “fastest cognitive route”, and that such a route corresponds powerfully to aggregate cyclist volume. This can be a useful tool for planners and designers tasked with making cyclist policy or building cyclist networks. Furthermore, segment angular analysis can be conceptualized as a quantifiable perceptual attribute which emerges from the system itself (independent of individual preference), and can thus be added to the link attributes in traffic simulation models. This offers the potential of improving such models’ accuracy and reliability while simultaneously reducing their cost by eliminating the O-D estimation phase.

5.2 Implications for Cyclist Planning

It is not difficult to see what cycling is such an important part of the sustainable transport agenda. Cycling has been found to have a wide range of public health benefits (29), environmental benefits (30) and economic benefits (31) - with over 200 million adults cycling each month in the UK alone. It is therefore important that cyclist planning has strong evidence-based approaches to guide its policy directions.

This study revealed findings that offer a more useful alternative to the current philosophy cyclist policy, as outlined above. Accessibility planning for cyclists should avoid overstressing travel time and shortest distances and should instead consider a more sophisticated “fastest cognitive route” hierarchy model. Such a model would be based upon probabilistic route choice and emergent, system level phenomena, but would be flexible enough to encompass individual variation in route choice preference.

Such a policy approach would have two steps (a) route set generation (based on angular segment analysis) and (b) route choice given the set (based on aggregate cyclist volumes). In the first stage, planners would conduct an angular segment analysis to identify the “fastest cognitive routes” from all points to all points. This would then guide the second step, which would be to create a hierarchical network of route choices that offer direct, parallel, and easy alternatives in order to accommodate a variety of environmental conditions which may influence route choice on the individual level. This combined approach captures the guiding logic of aggregate cycle behavior (angular minimization, as demonstrated in this study) while still offering a variety of route choices for the individual cyclists.

5.3 Suggestions for Future Research

The current study examined only cyclist weekday volume counts and revealed preferences of journey to work trips. An essential extension of this study would necessitate extending the research to include leisure trips and to compare them with weekend cyclist volume counts. A

wider selection of data in alternate contexts would also provide additional evidence to test the claims of this study.

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