Exploring the utility of the spatially-constrained accessibility measure in integrating urban cycling and land-use in Pune, India
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EXPLORING THE UTILITY OF THE SPATIALLY-CONSTRAINED ACCESSIBILITY MEASURE IN INTEGRATING URBAN CYCLING AND LAND-USE IN PUNE, INDIA

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ABSTRACT

Urban cycling in many developing cities is greatly hindered by the physical barriers occasioned by the dichotomous approach to urban land-use and transport planning. This divided approach to planning engenders urban forms that are incompatible with the cycling needs, thus making cycling unsafe and unattractive. While this is so, literature suggests that the concept of accessibility offers a useful framework for integrating transport and land-use. However previous studies have not explicitly investigated the impact of physical barriers to accessibility. This article develops a spatially-constrained accessibility measure and explores its utility in integrating urban cycling and land-use. Revealed and stated preference data is analysed to find out the cycling behaviour and patterns as well as the physical factors that inhibit cycling in Pune. The results of this analysis enable the study to calibrate an accessibility measure that takes cognizance of the physical barriers that stifle cycling. A key finding of the study is that the spatially-constrained accessibility measure can enable different levels of accessibility in different parts of a city to be estimated under different land-use scenarios. Accessibility indices derived from this kind of modelling can also offer a common basis for land-use planners and transport planners to prepare plans that are sensitive to both cycling and land-use needs. The article identifies the need for empirical studies that deliberately single out the exact sections of the city roads that constitute barriers to cycling in order to make the measure more useful.

KEYWORDS

barriers to cycling, accessibility, land use –transport integration

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INTRODUCTION

Urban cycling can contribute to ameliorating the current urban transport challenges facing developing cities if it is well integrated into urban transport and land-use planning system (Mohan, 2001; Pucher, Korattyswaropam, Mittal, & Ittyerah, 2005; Srinivasan & Rogers, 2005). This is however scarcely the case in most of these cities (Mohan, 2001; Pucher, et al., 2005; Srinivasan & Rogers, 2005). Current researches show that urban land-use and transport planning has instead engendered physical barriers that frustrate rather than promote cycling (Handy & Clifton, 2001; Olvera, Plat, & Pochet, 2003; Pucher, Komanoff, & Schimek, 1999). The difficulty of dovetailing urban land-use planning on the one hand and urban transport planning on the other hand has in part been presented as an explanation to this situation (Curtis & Scheurer, 2010; Tennøy, 2010). Tennøy (2010) for instance points out that conflict in framing urban transport problems between urban land-use planners on the one hand and transport planners on the other hand poses a great drawback in integrating transport and land-use.

While the foregoing is the case, current accessibility studies suggest that the solution to urban transport challenges rests in addressing accessibility rather than mobility concerns. The traditional urban transport focus on mobility has thus been challenged (Bertolini, le Clercq, & Kapoen, 2005; da Silva, da Silva Costa, & Macedo, 2008; Iacono, Krizek, & El-Geneidy, 2010). There is a consensus that the contemporary urban transport challenges are better addressed by shifting attention to the underlying reasons that trigger the need for trip making. In this regard, Bertolini et al. (2005) point out that a well-defined concept of accessibility offers a useful framework for integrating transport and land-use. The authors note that the concept can directly be related to the quality of transport and land use systems on the one hand and social, economic and environmental goals on the other hand.

This paper extends the foregoing debate by looking at the effects of physical barriers on accessibility. It argues that accessibility modelling for cycling in developing cities must compensate for physical barriers if it is to be useful in aiding cycling and land-use integration. To this end, the paper takes a case of Pune, India and develops a spatially-constrained accessibility measure in order to explore the utility of the measure in integrating urban cycling and land-use. The paper begins by analysing the cycling patterns and behaviours in Pune. A further analysis of the spatial configuration of Pune is carried out with a view to finding the connection between the cycling patterns and behaviour on the one part and the land-use pattern of the city on the other. Finally, an accessibility model that is constrained by the barriers to cycling is calibrated. This measure enables the study to draw conclusions regarding cycling supportive infrastructure development and policy for a typical developing city.

THE NEXUS BETWEEN URBAN CYCLING AND LAND-USE

It has been argued that deliberate efforts must be made at understanding the co-influence between urban land-use and transport strategies on urban transport and land-use respectively if a sustainable solution to the current urban transport challenges is to be found (Banister, 2008; Bertolini, et al., 2005; Curtis & Scheurer, 2010). The work of Wegener and Furst (1999), Cao et al. (2007) and Zhao (2010) invariably points out that urban land-use strategies impact on key urban transport indicators like trip length, trip frequency and mode choice. It is evident from their work that urban land-use planning shapes urban form through the location, distribution and densities of opportunities thereby influencing people's travel patterns. Wegener and Furst (1999) for instance positively correlate higher densities of employment to average trip lengths. At the same time, a mix of workplaces and residential land-uses with shorter trips are seen to have a positive impact on physical transport modes like cycling and walking (Cao, et al., 2007; Wegener & Furst, 1999). From a transport point of view, studies have shown that transport strategies influence urban land-use patterns by altering accessibility at different locations. Bertolini et al. (2005) and Wegener and Furst (1999) for instance note that higher accessibility increases the attractiveness of a location for all types of land-uses, consequently influencing the patterns of new urban development.

Urban transport infrastructure and their functional space allocation to different modes of transport have also been found to influence travel costs, travel time, safety and accessibility (Hunt & Abraham,

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2007; Pucher, et al., 1999; Rietveld & Daniel, 2004). Roads that have separate cycling paths or that allow lower car speed are perceived to be safer and therefore more cycled compared to those that are perceived to expose cyclists to accidents (Hunt & Abraham, 2007; Pucher, et al., 1999; Rietveld & Daniel, 2004). Interestingly however, Rietveld and Daniel (2004) challenge the conventional assumption that the provision of cycling infrastructure alone is enough to promote cycling. According to the authors, provision of cycling infrastructure must be coupled with supportive urban land-use planning policies that encourage cycling. This argument is echoed by Pucher et al. (1999) who underscore the need for higher density developments of mixed uses in order to encourage cycling. It is implicit from these authors that reasonable distances are necessary to make urban cycling attractive.

In spite of many researches that have attempted to understand the influence of transport infrastructure on cycling, there is still lack of a rigorous analysis of the transport network and urban land-use factors that determine the amount of cycling (Raford, Chiaradia, & Jorge, 2007). The authors conclude that route accessibility plays an important role in cyclists' route choices. An important contribution of their study is that cyclists tend to choose the fastest routes rather than just the shortest routes as often assumed. While this is so, Parkin, Wardman and Page (2007) have identified a lack of bicycle lanes as well as motor traffic speed and volumes as some of the key determinants of cycling patterns and behaviour that shape route choice. Travel (cycling) patterns and behaviour include trip frequency, destination choice, mode choice and trip complexity among characteristics. Parkin et al. (2007) have pointed out that cycling behaviour and patterns are the results of the perceived safety among cyclist and that these are central in determining whether they will cycle on given routes. In view of this, it is evident that an urban land-use pattern that is focused on achieving land-use mix alone cannot realize integration between urban cycling and land-use; additional efforts have to equally focus on removing the perceived barriers to cycling.

It is evident therefore that the meeting point between urban cycling and land-use lies in urban configurations that reduce cycling distances and the physical efforts while at the same time offering the safety that cyclists need to overcome the spatial separation between trip origins and their opportunities. In this regard therefore, urban land-use patterns must be viewed not just as the relationship between trip origins and destinations but also as the conditions on the routes that link them. These must be taken into account in order to adapt transport infrastructure planning to the cycling needs.

METHODOLOGY

DATA AND DATA PREPARATION

The study used data from Pune, India. This comprises census tract data, road network data, household survey data, road network survey data and a land-use map of 2006. The census tract data included both shapefile as well as the attribute data of 144 wards of Pune. The relevant attributes of this data for the current article included the area of the city, administrative boundaries, density of trip destinations such as schools and employment, density of cycling trip production and attraction and the land-use classification based on Pune Development Plan of 2006. On the other hand, the road network data included the permitted car speed, road classification and the length and widths of the roads. The stated (SP) and revealed (RP) preference data on the other hand included the socio-economic characteristics of (potential) trip makers, destinations cycled, distances cycled, routes cycled and the reasons for such route choices.

Revealed and stated preference data obtained from household and road network survey data were coded and input into the Predictive Analytic Software (PASW) format. Coding in this case aimed to enable the SP and RP data to be linked to the spatial database in ArcGIS in order to facilitate spatial analysis in ArcGIS and PASW.

From the census tract data and land-use map of 2006, new Transport Analysis Zones (TAZs) were created that were realistic to short cycling distances that were realised from the analysis of cycling

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behaviours from SP and RP data. The aim of creating new TAZs was to create homogenous zones that could be useful in spatial analysis of the cycling patterns and behaviour.

In view of the fact that cycling was only possible over shorter distances, the study reduced the geographical scale of the census tract data to allow realistic analysis. To this end, data relating to the population, education opportunities, employment opportunities, cycling trip production and cycling trip attractions was disaggregated to the new TAZ. The researchers assumed that the distribution of these elements was uniform across each of the entire census tracts. The formula given in equation 1 below was used:

$$X = \frac{x_n}{A} \, x \, a^1$$

Equation 1

Where: $X =$ Disaggregated value of population, education opportunities, employment etc. in a TAZ;
$x_n =$ Value of the element in a ward before redistribution;
$A =$ Total census tract area (before creation of TAZ);
$a^1 =$ Area of new TAZ;

The resulting data from the above operation contained the TAZ characteristics that were needed in the subsequent modelling of accessibility.

From the road network data, the study created a cycling network to represent the supply capacity for cycling in the study area. This network was specifically used in the network analysis to calculate distances between the trip origins and destinations. The length of the segments in this case represented the distances cycled. Cycling was assumed to take place on the same roads used by cars. This assumption was guided by the work of Mohan (2004) who has shown that a good amount of cycling in Indian cities takes place on some of these roads.

Bicycle routes were created from the road network data in ArcCatalog 10 platform.

ANALYSIS OF CYCLING PATTERNS AND THE UNDERLYING URBAN FORM

The stated and revealed preference data was statistically analysed in order to obtain the prevailing cycling patterns and behaviours. These patterns and behaviours were required as the input for accessibility calibration. In analysing data from the stated preference survey, deliberate focus was on the responses given by the active cyclists. These responses reflected the true, rather than hypothetical cycling behaviours and patterns. Nonetheless, responses from the potential cyclists were also analysed in order to examine the effects of physical barriers on cycling. In this latter case, the analysis focused on identifying the reasons that barred the respondents from cycling.

To begin with the study carried out a Frequency analysis and percentages analysis in which the respondents were summarised according to their trip origins and destinations. This enabled the study to find out the trip origins and destinations. A cross-tabulation analysis was then carried out between land-use activities and trip origins and destinations. The aim in this case was to find out the land-use activities at trip origins and at trip destinations. The study then carried out a cluster analysis on different land-use activities. The aim was to find out the spatial distribution of these activities and to assess if the distances created by their distribution were conducive to the distances that cyclists were willing to cycle. A spatial regression analysis was therefore carried out in order to relate the density of cycling trips generated and attracted to different zones and the density of opportunities available at these zones. A spatial analysis of the population of cyclists at the residential zones enabled their spatial distribution to be recognised. Similarly, the density of employment and education facilities enabled the spatial distribution of opportunities to be recognised. A weighted least squares method was used to estimate the attractiveness of the zones on the basis of opportunities like schools and employment. Polynomial regression analysis on the other hand enabled the study to find the effects of distance on the proportion of cycling trips and to fit a model for estimating the response of cyclists to increases in distances between trip origins and destinations.

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Finally, a multiple regression analysis on the volume of cycling and factors like car speed, volume of cars and buses and size of the carriageways was also carried out. This analysis purposed to find out which roads characteristics constituted barriers to cycling.

The results of the above analyses gave the input into accessibility calibration. The calibration was based on Hansen (1959) equation (Equation 2).

$$A_{i=} \sum_{j=1}^{n} D_j \, e^{-\beta C_{ij}}$$

Equation 2

Where:

A_i is a measure of accessibility of zone *i* to all opportunities, D in zone *j*;

C_{ij} is the cost of travel between *i* and *j*, (in this case taken as the distance between the two points); and

β is a cost sensitive parameter of distance decay.

The function was implemented as an O-D cost matrix in the Network Analyst extension of ArcGIS as explained later under model calibration.

RESULTS

CYCLING PATTERNS AND BEHAVIOUR AND THE RELATION TO URBAN LAND-USE PATTERNS

Figure 1 compares the contribution of different trip origins to the amount of cycling in the study area. These results were obtained from frequency and percentages analysis. On the other hand, figure 2 shows the density of land-use activity at cycling trips origins. These results were obtained when the trip origins obtained from frequency and percentage analysis were joined to their corresponding spatial data and subsequently analysed for the density of land-use. This analysis was carried out to enable the study estimate the contribution of each of these land-use categories to cycling production. Attention was paid to identifying the land-use category and the density of each of these land-uses.
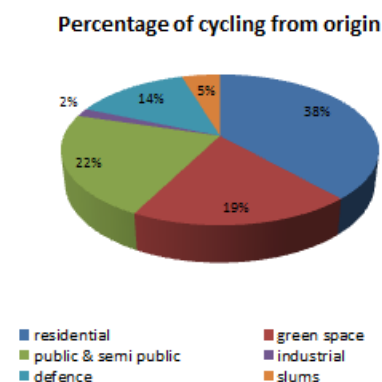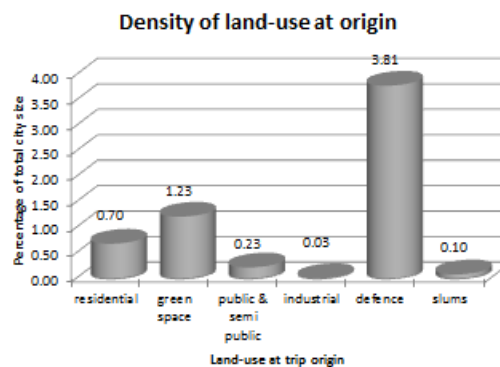

Figure 1: Percentage of cycling from origin

Figure 2: Density of land-use at trip origin

This analysis shows that the majority of cyclists have their trip origins as the residential areas. Formally recognised residential areas and the slums produced about 43% of all cycling trips. This finding led the researchers to assume that all trips originated from the residential zones for purposes of accessibility calibration. Trips produced from the other land-use categories were consequently

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assumed to be return trips to the residential places. In terms of the city's land-use structure, it is interesting to note that while residential areas accounted for the majority of trip origins, the total density of residential areas where cyclists came from was only less than 1% of the city's total area. The probable reason attribute to this finding was that only roads to a few residential places in the city were safe to cycle. Alternatively, this finding could imply that cycling trips originated from particular residential places, probably slums and low income areas where the captive cyclists comprised the majority of the residents. This assumption is informed by the work of Mohan (2004) who has documented the presence of captive cyclists on many roads of Indian cities.

In order to determine the trip destinations on the other hand, the reported trip destinations from the revealed preference survey were identified. These were then summarised by frequency in order to determine how popular they were among cyclists. Table 1 below gives the results of this frequency count.
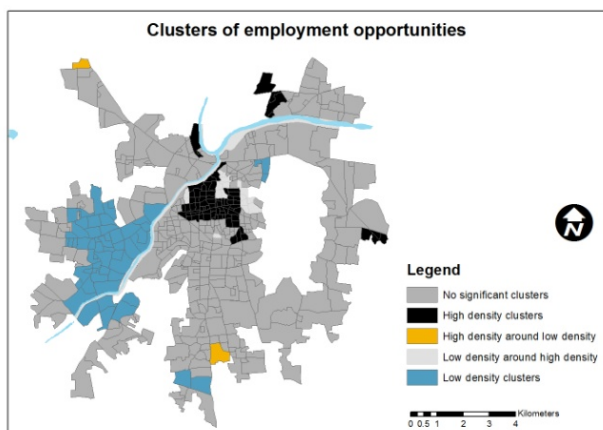
Table 1: Trip destinations

Trip destination	No. of cyclists	Percentage
Hawker/ vendor	3	1.1
Factory	9	3.3
Shop/ commercial	21	7.69
House	21	7.69
Office	28	10.26
Roadside/ informal	9	3.3
School/ college	*145*	*53.11**
Others	37	13.55
Total	**273**	**100**

* *Most cycled destination*

According to the results presented in table 1 above, it is evident that most cycling trips ended at schools and work places. Educational institutions comprised the destinations that were most cycled to, accounting for over 53%. This was followed by work destinations, which attracted about 26% of cycling. Internal cycling within the residential areas attracted only 8% as trip destinations while other destinations accounted for about 14%.

In order to assess how supportive the existing land-use pattern was to cycling between these origins and destinations, a cluster analysis of the densities of employment and education opportunities was carried out. This analysis aimed to find out the pattern of distribution of trip origins and destinations across the urban space. Dissart and Vollet (2011) have shown that the cluster analysis can be used to analyse for spatial patterns such as the relationship between landscape and employment. Figure 3 below shows the results of the cluster analysis of employment opportunities.


[fig. 3] Clusters of employment opportunities

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It is evident from the above figure that most employment opportunities were clustered at the centre of the city. There were also clusters of high density employment towards the north of the city, just after the confluence of River Mulla and Mutha as well as to south eastern side of the city. These are shown by the black TAZs in the figure above. The western side on the other hand did not have much employment as seen from the clusters of low density employment opportunities neighbouring each other. A better part of the city however did not have any striking significant clusters of employment opportunities.

This pattern of land-use organisation implies that while cyclists who lived near the areas of high clusters of employment could easily cycle to work, their counterparts from farther away had to cycle longer distances in order to access the same job opportunities. This provokes an interest to find how distance between origin zones and opportunities influenced the ability of cyclists to partake in these opportunities. It is equally interesting to find out how barriers to cycling impacted on the ability of cyclists to get to opportunities that were clustered only at a few places in the city.

In order to confirm if there was any relationship between cycling and these opportunities, a spatial regression was carried out on the density of cycling attracted at the zones and employment and education opportunities. According to Fotheringham, Brunsdon and Charlton (2002), the geographical weighted regression could be used in such situations to predict variables by fitting a regression equation on every zone in the dataset. The geographical weighted regression achieves this by searching for explanatory variables that fall within the bandwidth of the dependent variable. In this case, density of cycling attracted to a zone was taken as the dependent variable while education and employment opportunities were taken as the explanatory variables. The default bandwidth of 2021 neighbours that was generated by the software was accepted in order to determine the number of neighbours for the estimation. This bandwidth was accepted because it allowed the density of cycling in all parts of the city to be related to the explanatory variables. Figure 4 below shows the result of this analysis.
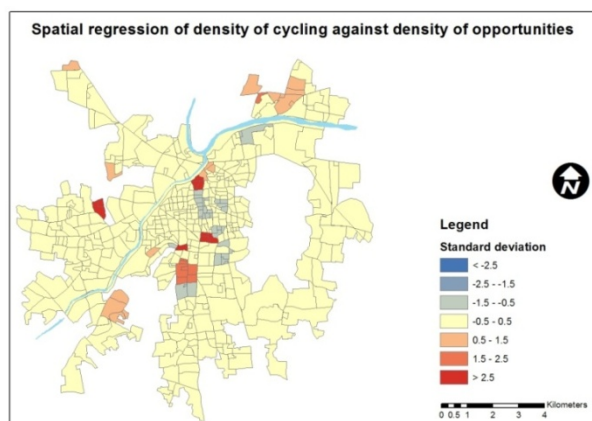

[fig. 4] Assessing the relationship between cycling and opportunities

The results reveal a positive correlation between the density of cycling attracted to the zones and the opportunities available in those zones. An R^2 value of .88 was obtained indicating that the density of cycling attracted could be well explained by the amount of opportunities at a zone. The dominance of zones with a standard deviation ranging between -0.5 to 0.5 shows that changes in the densities of opportunities went hand in hand with changes in the amount of cycling attracted to the zones. There were however a few zones that showed clusters with a large standard deviation that was greater than 2.5 or lower than -2.5. These were assumed to be insignificant in view of the fact that only 8 out of all the 474 TAZs showed this large standard deviation.

Given the findings presented above, it was interesting to find out the pattern of distribution of people on the other hand in order to relate this to their ability to access these opportunities. A cluster analysis was done to achieve this. Figure 5 shows the results of this analysis. The results reveal that the distribution of population was evidently densely clustered near employment opportunities. The

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patterns also reveal a striking spread of population across the entire city landscape as seen from the predominance of the grey colour. This raises questions about how easy it is to cycle from the far-flung zones to places of work and education, most of which are clustered at the central part of the city.
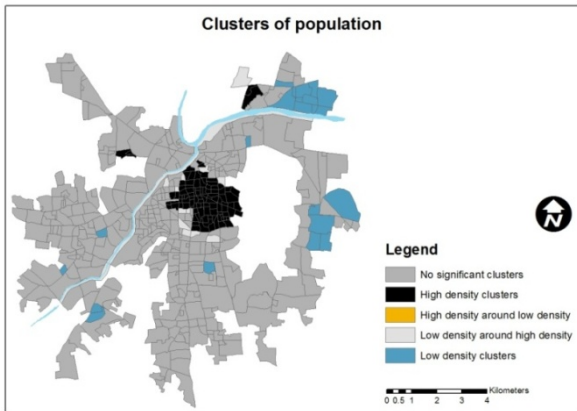
[fig. 5] Clusters of population

The situation with regard to education opportunities was not any different from that of employment. In this case, a similar distribution pattern to that of employment opportunities was observed (Figure 6). The distribution of schools is again seen to be clustered at a few specific zones in the city. This imposes similar cycling demand on residents who live away from these opportunities. This again raises curiosity about their ease of cyclists who live farther away from these clusters to get to them.
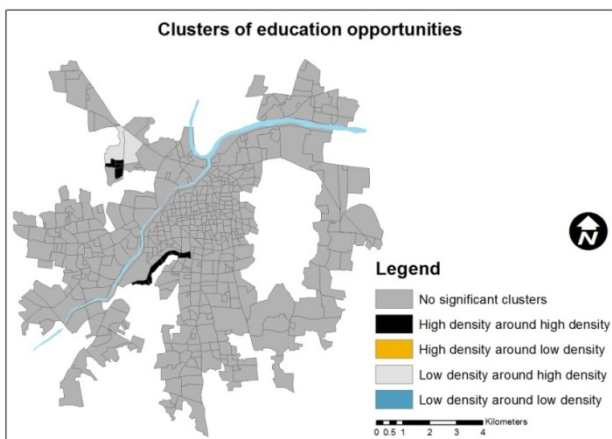
[fig. 6] Clusters of education opportunities

In view of the foregoing results, the study considered that the distance between the opportunities and residential areas imposes an important constraint on accessibility for cyclists. The effect of distance on the amount of cycling is assessed in the proceeding part.

EFFECTS OF DISTANCE ON THE AMOUNT OF CYCLING
The distance cycled was considered as an important indicator of how easy it was to get from the trip origins to the opportunities located at different places in the urban space. Highly clustered opportunities were taken to engender longer travel distances while dispersed blend of land-uses was taken to lead to shorter cycling distances.

In view of this assumption, the distances cycled were analysed in order to determine the effects that they had on the amount of cycling. The analysis sought to find out the mean, modal as well as the minimum and maximum distance that were cycled. This analysis also aimed to enable the study to estimate the co-efficient of distance as a cost factor to cycling in Pune city. Table 2 below shows the results of the analysis of distance cycled.

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*Table 2: Statistics for distance between origins and major destinations*

Valid cases	273
Missing cases	0
Mean	2.98
Mode	2
Minimum	0
Maximum	6

From the results presented, it is evident that cycling was possible for distances of up to 6 km from the trip origins. Distances of 0km were realised in the case of intra-zonal trip makers. On average however, the majority of the respondents could only cycle up to 2.98 km while the modal distance cycled was 2 km from the trip origins. This rather short distance cycled suggests that majority of cyclists could only cycle to opportunities that were not far from their places of residence. Alternatively, this pattern could also be attributed to the existence of barriers imposed by highways that were unsafe to cycle across. These highways thus restricted cycling to only a limited area from the trip origins.

Given these findings, the accessibility model presented in this paper took 6 km from the trip origins to be the cut-off beyond which no accessibility could be realised. In this sense, distance itself was taken as a barrier to cycling since opportunities that were located more than 6 km from trip sources could not be accessed. This effect is modelled later under model calibration.

The foregoing cycling behaviour was relevant in enabling inferences to be made about accessibility at different zones once the distances from origins to destinations were determined using the Origin-Destination cost matrix presented later in the accessibility model.

The observed relationship between cycling distance and proportion of cycling further enabled the study to determine the distance decay function to use in modelling accessibility. To do this, a scatterplot was prepared that related the percentage of cycling and the distances cycled. This was done in Microsoft Excel. Polynomial regression of order 5 was then used to fit the resulting curve that approximated the cyclists' reaction to increasing distances from trip origins. Even though the polynomial regression has a wavy characteristic between data points, it nonetheless fitted the cycling pattern observed in Pune since the maximum distance was only limited to 6km from trip source. The wavy characteristic of the polynomial regression was not evident within the range of 6km. Figure 7 shows the results of this operation.
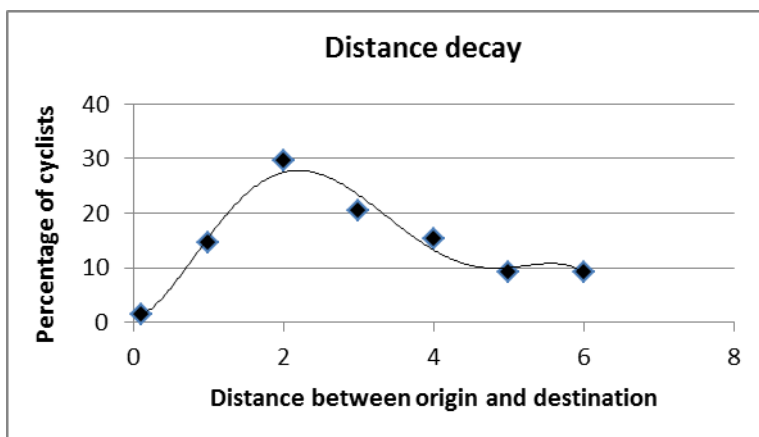
[fig. 7] Relationship between distance and percentage of cyclists

The model in figure 7 above yielded the following function to fit the pattern observed above.

$$y = -0.1699a^5 + 2.6682a^4 - 13.97a^3 + 24.393a^2 + 1.7659a + 0.885$$

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Equation 3

In this case, **y** is the percentage of expected cyclists while **a** is the distance from trip origin to the destination. The curve could explain up to 96% ($R^2 = 0.9612$) of the possibility to cycle and was therefore adopted in estimating the percentage of possible cyclists in the accessibility model developed later.

WHAT POTENTIALS ATTRACT CYCLING TO TRIP DESTINATIONS?
In order to find the factors that attracted cycling to different destinations, the study correlated the amount of cycling attracted to the zones with the population density, density of employment and education opportunities at each TAZs. The results presented in table 3 below were obtained. These factors that attracted cycling to different destinations were required in order to calculate zone potentials for use in accessibility modelling. This latter part is done under accessibility modelling.

Table 3: Correlation between amount of cycling attracted and the opportunities (N=475)

	Density of cycling attracted	Population density	Employment density	Education density
Population density	.192**	1		
Employment density	.092*	.382**	1	
Education density	.932**	.112*	.062	1

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

The results show that there was a significant positive correlation between the densities of cycling attracted at different zones and the density of employment and education opportunities. Education opportunities had the highest correlation with cycling. This identifies with the previous finding presented in table 1 where it was shown that education facilities were the leading trip destinations. Cycling attraction was also correlated with the higher population densities. This could probably be because of the kind of activities that cyclists took part in. As shown in table 1, hawking and other informal trading activities comprised some of the trip destinations among the cyclists who were interviewed in the revealed preference survey. The study reasoned that these activities were dependent on the presence of people for their markets. In view of these findings, it appears that land-use planning led to concentration of opportunities at the core of the city thereby making the area more attractive to cyclists when compared to other parts of the city.

The densities of these opportunities were mapped in an effort to enable an understanding of their spatial distribution and to enable inferences to be made regarding their influence on accessibility on the basis of their distribution patterns.

In terms of cycling therefore, the patterns revealed by these analyses suggest that people who live outside the central part of the city would have to cycle longer distances in order to access opportunities at the city centre. These can only be possible for people who live within 6 km of the city considering the findings already presented in the previous section.

URBAN FORM FACTORS THAT INHIBIT CYCLING
The preceding parts have presented the cycling patterns and behaviours together with the underlying urban land-use patterns that are thought to dictate them in Pune. This current part now looks at the physical barriers that are caused by the way the roads are organised. The combined impact of both land-use patterns and road design are seen in this study to be responsible for constraining accessibility in the city. The current part analyses the permitted speeds of motorised transport, the sizes of the carriageways and the number of uncontrolled access. The volumes of motorised transport, pedestrians and the number of informal activities alongside the roads are also analysed as they were considered to be indicative of the manner of the city's land-use planning. The study argues that the concentration of activities at particular places in the city leads to higher volumes of cars and people around such places.

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A multiple regression analysis was carried out in order to find out whether the factors that were thought to impede upon cycling indeed did so. The regression analysis related these factors with the volume of cycling along and across the roads. The results shown in table 4 below were realised.

Table 4: ANOVA test for significance of relationship between urban form and cycling

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	768389.294	11	69853.572	36.889	.000[a]
	Residual	1030137.872	544	1893.636		
	Total	1798527.165	555			

a. Predictors: (Constant), hourly volume of auto, number of parked vehicles at link(NMV, autos, etc), number of uncontrolled vehicular access, average car speed, size of carriageway in meters, number of informal activities (hawkers, vendors etc), hourly volume of buses, hourly volume of pedestrians, average bus speed, hourly volume of cars, average speed of three wheeler
b. Dependent Variable: hourly volume of bicycles and non-motorised vehicles

The regression analysis yielded a test statistic of 36.889 and a p-value of .000 which suggested that at least one of these factors impeded on cycling in the city. A t-test was then carried out for each of the independent variables to see if they had a significant relationship with the cycling volumes.

According to the results obtained from the analysis, some factors like the number of pedestrians showed positive correlation with amount of cycling while others like the average car speed and the hourly volumes of cars showed negative correlation with cycling. By looking at the significance of the statistics returned, the study was able to identify which factors correlated significantly with cycling. The average car speed with a coefficient of -.72 and a p-value of .007 seemed to exert the strongest negative influence on the volume of cycling and was therefore of much interest in the context of the current study. It seems roads that are designed to permit higher car speed were therefore risky for cycling. Parkin et al. (2007) have shown that such routes are in most cases avoided by cyclists due to the perception that that they expose cyclists to accidents. The results from the hourly volume of cars similarly appear to suggest that wider roads that permit larger volumes of cars also made it hard to cycle. In this case, a coefficient of -.04 was realised with a p-value of .045. Other indicators of urban form that equally seemed to impact negatively on cycling included the number of uncontrolled vehicular access (coefficient of -.389; p-value .349) and the size of the carriageway (coefficient of -1.938; p-value .057). However, these were found to be statistically insignificant.

On the other hand, contrary to the expectation of the study, the hourly volume of pedestrians, the number of informal activities, the bus speed and volume of bus were found not to inhibit cycling. All these predictor variables resulted in positive coefficient which implies that volumes of cycling increased as these variables increased. This probably suggests that most of the cyclists were captive cyclists who were themselves participants of informal activities and other land-use opportunities that attract pedestrians and commuters who use the buses.

In terms of modelling accessibility at different trip origins therefore, the study has given attention to the permitted car speed on the roads. The model developed later in this work assumes that the volume of cars exerts uniform impedance on cycling across the zones due to lack of data to model its impact on accessibility.

ACCESSIBILITY MODELLING

This section forms the climax of this article. It draws from the findings presented in the preceding section to model accessibility at various origin zones. The section is organised in 3 parts; the first part puts together the variables used to calculate the zonal potentials and the distance decay function in the model. The distance decay function takes distances between origins and their corresponding destinations as the cost factor. The second part presents the model calibration. The part sets off by giving the assumptions of the model. The section culminates in the third part where the results of accessibility measure are presented. These results are mainly influenced by the manner in which land-

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use in the city is organised. In order to link these with transport, the study analyses the resulting accessibility patterns using the network indicators to find out the impact of the road barriers on accessibility.

CALCULATING THE ZONAL OPPORTUNITIES AND DISTANCE DECAY FUNCTION
The results from the previously presented analysis revealed a positive correlation between the amounts of cycling attracted to the zones and their population as well as employment and education opportunities.

On the basis of the relationship revealed by these results, a regression analysis was carried out to fit a model that could be used to explain the influence of the above variables on the potential at each of the zones. Equation 4 below was used to aggregate the potential of the zones.

$$D_j = f(P_{ar} + P_{op} + E_{mp} + E_{du})$$

Equation 4

Where:
- D_j = potential of TAZ *j*,
- P_{op} = population density at TAZ_j,
- E_{mp} = Employment density at TAZ_j and
- E_t = Density of education opportunities at TAZ_j

Accordingly, the potential of each zone was thus derived from the regression function shown in equation 5 below. It should be pointed out that the resulting value from this calculation is a scale value that only enables comparison of the potential of the zones.

$$D_j = 0.004 + 0.096 x P_{op} + 0.005 x E_{mp} + 0.392 E_{du}$$

Equation 5

The potential of each zone was calculated and visualised in ArcGIS10 using the above function. Figure 8 below shows the results of this operation.
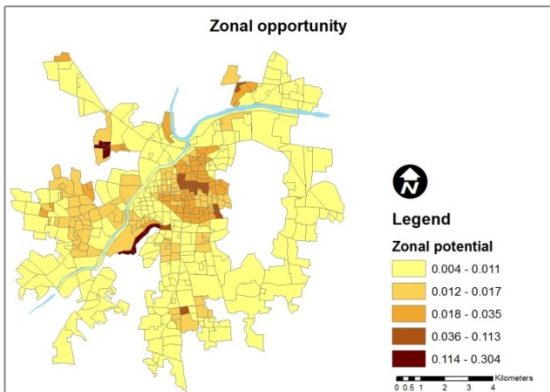
[fig. 8] Aggregated zonal opportunity

Figure 5-1 shows that the opportunity of the zones decreases from the city centre. This result identifies positively with the results of analysis of the densities of the opportunities that cyclists partake. Some linear urban developments can also be seen which closely follow the roads. It is evident therefore that areas where land-use planning had engendered more opportunities similarly attracted more cycling to themselves.

On the other hand, the inverse relationship between the amount of cycling and distance between trip origins and destinations (equation 3) informed the choice of the distance decay function. This function is presented in equation 6 below. The function fitted the proportion of cycling to the pattern observed when the effect of distance on the amount of cycling was assessed. Accordingly, the proportion of

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cycling peaked at 2km from trip origins before it gradually started to go down with every additional kilometre up to 6km.

$$F(C_{ij}) = -0.1699x^5 + 2.6682x^4 - 13.97x^3 + 24.393x^2 + 1.7659x + 0.885$$

Equation 6

MODEL CALIBRATION

A number of assumptions were made in the model presented in this section. These are listed below:

i.) All the roads with car speed below 50 km/h[1] are assumed to be cycleable;

ii.) The destinations are assumed to have adequate and acceptable opportunities to cater for the needs of all cyclists who can reach them;

iii.) The volume of cars on the roads is assumed to exert uniform impedance to cycling since there was no data to take its variation into account;

iv.) The cost of making turns is equal throughout all cycleable roads;

v.) It is assumed that roads with car speed of 50 km per hour impose a hard barrier to cycling. This is partly due to data limitations;

vi.) The observed percentage of cyclists per distance as depicted in figure 7 is representing the likeliness to cycle per distance.

Modelling was done through two parallel approaches that sought to bring together elements of urban land-use and urban cycling through the use of an accessibility measure. In the first case, the formula provided in equation 5 was applied to calculate the opportunities at each TAZ in ArcGIS10. This gave an output that represented the zonal opportunity for all TAZs in the entire area of study. On the other hand, an O-D cost matrix analysis was carried out on the road networks data to calculate the distances between origins and destinations that were visited. This analysis was done for the scenario without barriers and the scenario with barriers. In the first scenario, the model allowed cycling to any destination as long as it was not more than 6 km from the trip origin. In contrast, the second scenario barriers were imposed on some routes. This was achieved by modelling roads that permitted car speed of 50 km/h as barriers. These roads were deemed to be unsafe for cycling on the strength of the analysis carried out here and backed by similar reasoning from other studies like that of Parkin et al. (2007). Though they could have been modelled differently, data limitation dictated the researchers to model them as hard barriers. To achieve this, a layer of these roads was created and specified as the barrier input in the O-D cost matrix analysis. The finding already presented earlier regarding the maximum cycleable distances informed the choice of the cut-off of 6 km from trip origins. This cut-off was deemed to be the maximum distance beyond which no cycling was expected according to the model developed in this article.

The O-D cost matrix analysis yielded a table with several pairs of origins and destinations of different trip lengths. These trip lengths represented the cost of cycling between origins and destinations. The field identity of the trip origins of the O-D cost output were collated in MS Excel and linked back to the spatial data in ArcGIS using the corresponding field identity.

The opportunity maps and the output of the O-D cost matrix analysis were then joined in ArcGIS to make the TAZs that had both cost of cycling between origins and destinations as well as the opportunities that attracted cycling to these destinations. The results of this join operation contained the TAZ identity, the opportunity in the TAZ and the cost of cycling between the TAZs. This output was exported to MS Excel where accessibility at each of the trip origins was modelled as explained below. The following strategies were adopted to derive accessibility scores at each trip origin.

- The resulting trip lengths from O-D cost matrix were converted to kilometres by dividing them by 1,000 before they were modelled as the cost, C_{ij} of cycling between trip origins and destinations.

- The distance decay function was taken from the model fitted by equation 6 presented on page 13. The values of C_{ij} were put into the function in order to make the trip lengths between each O-D realistic to the effects of friction of distance;

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- The opportunities, D_j at each of the zones were taken from equation 5 on page 12.

The study proceeded to calculate accessibility using the Hansen's accessibility formula presented in equation 2. In this case, $F(C_{ij})$ replaced $e^{-\beta C_{ij}}$ in the accessibility model developed by Hansen (1959). As presented earlier, the former function fitted the cycling patterns in Pune better than the latter which we found to reflect motorised transport since it give too much weight to origins that were close by the destinations. The total accessibility at each trip origin was calculated by summing the product of all individual opportunities that could be reached from each zone and their corresponding exponent of the distance decay function.

Table 5 below presents a screen-print that shows how accessibility was modelled using the cost of cycling (C_{ij}), opportunities at trip destinations (D_j) and the distance decay function, $F(C_{ij})$.

Table 5: Calculation of accessibility at each origin

Q21		f_x	=SUMIF(C21:C4009,T21:T274,P21:P4009)								
G	H	I	J	K	L	M	N	O	P	Q	R
Cij	(-0.1699*Cij^5)	2.6682*Cij^4	(-13.97*Cij^3)	24.393*Cij^2	1.7659*Cij	0.885	Dj	F(Cij)	Dj*F(Cij)	∑Dj*F(Cij)	MYF_FID
0.00	0.00	0.00	0.00	0.00	0.00	0.885	0.00769537490	0.885	0.00681041	0.0068	0
0.00	0.00	0.00	0.00	0.00	0.00	0.885	0.00764759479	0.885	0.00676812	0.4144	1
1.05	-0.22	3.26	-16.22	26.95	1.86	0.885	0.00764759479	16.506	0.12623135	0.7373	3
1.10	-0.28	3.97	-18.82	29.76	1.95	0.885	0.00764759479	17.461	0.13353566	0.0145	4
1.21	-0.45	5.79	-24.99	35.94	2.14	0.885	0.00764759479	19.329	0.14782312	0.4536	5

## THE ACCESSIBILITY SITUATION IN THE CONTEXT OF LAND-USE DISTRIBUTION

The results show differing levels of accessibility between the two scenarios. Accessibility in the city was found to be better in the scenario with no barriers compared to the scenario with barriers. Accessibility was highest at the city centre where the scores went to the maximum of 301,424 when there were no barriers. However, with the introduction of barriers, the scores came down to only 23,976. It is notable that accessibility at trip origins that were close to the city centre remained comparatively better in both scenarios. These results identify with the earlier finding which showed that most opportunities were clustered at the centre of the city. It seems the concentration of opportunities at the city centre had a positive effect in shaping the cycling patterns in the city. Figure 9 below shows that accessibility at the central part was higher when there were no barriers. Higher accessibility levels could also be seen on the western side of the city centre, probably due to the same reasons.
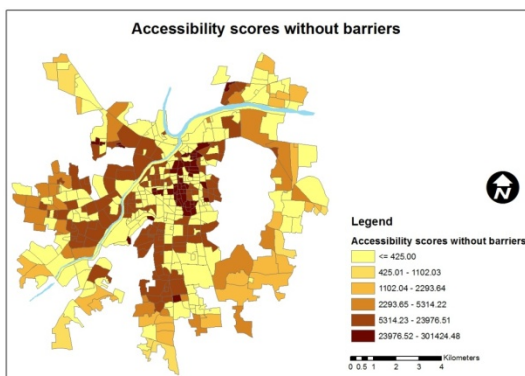
[fig. 9] Accessibility without barriers

However, with the incorporation of barriers, accessibility suddenly grew very thin as shown in figure 10 below. It is remarkable that accessibility scores in the range of 23,976 – 301,424 could no longer be achieved when barriers were introduced. The study related this to the fact that the barriers cut off a significant proportion of cyclists from reaching the destinations which they could otherwise do if cycling facilities were safe. Despite this, accessibility at the city centre and the western part of the city centre is again seen to remain relatively better when compared to the other zones. A possible reason for this could be that residential places that were near the city centre continued to enjoy better accessibility compared to their counterparts at the outskirts of the city which were now cut off by the

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barriers. It could also be possible that the areas had more cycleable roads compared to the other parts of the city.
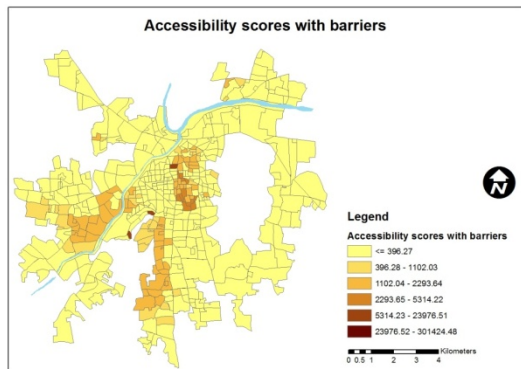
[fig. 10] Effects of barriers on accessibility

SUMMARY OF FINDINGS

The article shows that indeed urban cycling in Pune is related to land-use patterns as well as the perceived road safety for the cyclists. While opportunities that attract cyclists were found to be generally concentrated at the core of the city, the population of active and potential cyclists on the other hand was scattered in different parts of the city. This raised important questions regarding the ease of cycling to the city centre from the far-flung areas. In view of the revealed travel patterns that showed no evidence of cycling beyond 6 km, the study argues that distance between opportunities and places of residence was itself a barrier to cycling. The analysis shows a general decrease in accessibility in the entire city when barriers are taken into account. Interestingly though, the city centre still remained comparatively more accessible than the other parts of the city. The concentration of opportunities and the higher density of cycleable roads around this place have been presented as the possible explanations to this relatively higher level of accessibility. The findings of the study underscore the need for appropriate infrastructure on the one hand and supportive land-use pattern on the other hand if cycling in Pune is to be promoted.

At the same time, the findings demonstrate the applicability of a spatially-constrained accessibility measure in aiding decisions on integrated cycling and land-use planning. The measure is found to be capable of enabling different urban form scenarios to be analysed in order to find out their implications on urban cycling. The measure is also found to be comparatively stronger when the interest is in assessing land-use patterns and distribution and their implication on urban cycling. Furthermore, the findings demonstrate that developing cities face unique urban cycling challenges that can be explained by their urban form. These challenges can only be addressed if they are studied in their own context rather than transferring the findings from developed cities as has been the practice to date.

CONCLUSIONS AND RECOMMENDATIONS

Integrating urban cycling in Pune calls for the synergy of efforts between land-use planners and transport planners. In this regard there is need for an accessibility measure that provides a common understanding of the current challenges facing urban cycling in the city. This measure is important because transport and land-use planners have often understood cycling challenges from dichotomous points of view, which often do not lead to the integrated solutions. Yet cycling challenge is a mix of land-use and transport issues and thus must be looked at in a comprehensive approach. This paper concludes that the current approach to urban planning cannot address the cycling challenges of Pune and any other city that faces similar cycling conditions. Consequently, it is argued in this paper that the spatially-constrained accessibility measure presents a better approach to integrating urban cycling and land-use. Nonetheless, there is need to make the measure more accurate in measuring accessibility situation under different urban form scenarios. The current study only addresses two extreme situations - where there are barriers and where there are no barriers to cycling. Due to data gaps, the

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study falls short of looking at the intervening urban form conditions between the two extreme conditions.

This paper also observes that the current theories upon which transport and land-use integration is based are also limited in terms of their capability to explain the relationship between cycling and land-use in the context of developing cities. For instance, barriers faced by cycling in developing cities do not seem to have been taken into account by the current theories. In view of this, the paper recommends the need for more investigation into the effect of barriers on urban cycling in order to determine accurately how they influence cycling. The authors further recommend the need to investigate urban form conditions that are favourable to cycling. It is argued that this investigation is important to ensure that the relevant urban form issues that underlie urban cycling are addressed to make the current pursuit to integrate urban cycling in developing cities successful.

The study reveals a close link between accessibility for cycling socio-economic variables like income in order make accessibility scores developed relevant in terms of aiding decisions regarding prioritising and targeting areas in need of bicycle infrastructure provision. It thus recommends the need to develop a method for identifying urban forms that are not only responsive to cycling but also more inclusive, economically affordable and less vulnerable environmental challenges posed by climate change.

Finally, there is need to collect data in order to validate the accessibility results that were realised in the current study. These will also be important in detecting the elements of the model that need to be adjusted to make it more accurate for supporting urban cycling and land-use integration decisions in future.

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