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Axial Analysis: A Syntactic Approach to Movement Network Modeling

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Abstract

This article shows how space syntax researchers have developed an alternative model for traffic assignment only by analyzing the accessibility measures of settlement roads. Numerous cases of traffic estimation, pedestrian and vehicular, have been delineated using the axial line method of space syntax analysis. The conclusion strongly suggests that space syntax can be an appropriate approach to traffic assignment for the densely populated cities of India where the absence of OD trip-data often poses problems in calibrating and applying the classical models for movement network modeling.

1. INTRODUCTION

An understanding of the multidisciplinary approach to dealing with the contemporary urban problems develops a new horizon in urban research: urban technology — a set of techniques that are used to derive sustainable and economical urban development solutions with data based evidence. Because the concern of urban development brings the issue of consequences or impacts on the city's socio-environmental landscape, the role of this approach, as a tool to evaluate the development benefits with evidence, is significant in the present context, and is thus an emerging approach.

Among many technological developments in the field, the theory of space syntax is considered to be a tool for the development and evaluation of urban planning and design policies. The theory of space accessibility analysis or space syntax (Hillier and Hanson, 1984) at different levels of urban environments was first developed at the University College London in the 1980s with an objective to understanding the complexity of spatial arrangement in urban morphology and its effects on urban life. Studies suggest that the algorithms of space syntax have the ability to foresee the development impacts with data-based evidence. Urban researchers (Hillier 1998; Peponis, Ross and Rashid 1997; Caria, Serdoura, and Ferreira 2003; Eisenberg 2005 and many others) have shown that along with other applications, space syntax can also be a good predictor of movement, and this approach is significantly less cost intensive and more time efficient than the contemporary transportation demand models.

Apart from the cost and time involved in collecting origin-destination (OD) trip-data needed for calibrating and applying the classical models for traffic

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assignment, the homogeneity of these data occasionally becomes contentious because of the mixed land use pattern and mixed traffic systems, which are typically found in the densely populated cities of India. As a result, the transportation policies developed with these assignment results become less effective when implemented for the urban infrastructure developments resulting traffic delays because of severe traffic congestion, unsafe commutation, inability of making quick traffic management plans in the event of an emergency, and all together, less-effective utilization of transportation investments. In this context, traffic assignments with the syntactic approach appears to be greatly appropriate for densely populated cities of India, where the absence of OD trip-data often poses problems in calibrating and applying the classical models.

2. WHAT IS SPACE SYNTAX?

Space syntax describes a set of theories and techniques that analyze the topological relationships of settlement spaces. The topological relationships of urban spaces help quantifying the properties of space arrangements, such as distributedness, non-distributedness, symmetricity and non-symmetricity (Hillier *et al*, 1984). These properties make some space more integrated than others within given built environment, typically known as system. A space that is more integrated is, on average, closely accessible from all other spaces, and contrarily, one that is not, is a segregated space.

Space in real life is a series of shapes and sizes that are linked together to form an autonomous whole. Therefore, the primary task of a space syntax analysis is to identify the segments or units of spaces from this whole mass and to see how one unit or a unit space is connected to all others. Researchers have introduced different types of unit spaces in space syntax. Convex space and axial line of Hillier and Hanson (1984), segmented line and angular/new-angular segmented line of Turner (2001-2007), and continuity line of Figueiredo and Amorim (2005) are some examples of these units. Among all unit types, axial line has been predominantly chosen by the space syntax community to quantify the accessibility measures of settlement roads for traffic estimation. Axial line is a form of unit space. Assuming that the trip-makers' notion of movement is the average number of changes of the direction encountered on routes, not to specific destinations, but to all possible destinations (Penn, 2001), the only possible representation of a specified roadway structure or system appears to be the minimal set of lines that pass through the connecting roads within that system. Each line here is an axial line. The map that comprises all axial lines of a roadway structure is an axial map (Fig. 1).

The arrangement of the building blocks, shown in solid boxes in Fig. 1a, automatically generates the configuration of accessible unit spaces Fig. 1b or axial lines describing how the lines are topologically connected to one another

Fig. 1 Development of Axial Lines. (a) Settlement Morphology. (b) Roadway Structure Describing Accessible Unit Spaces. (c) Axial Map.

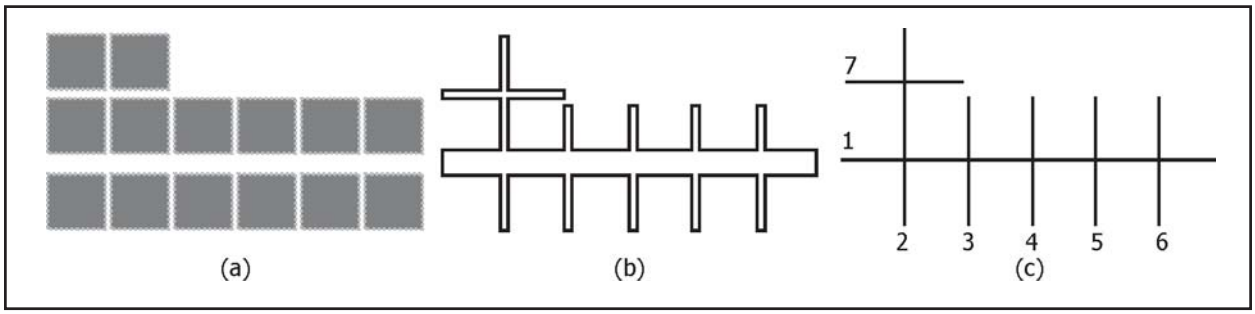
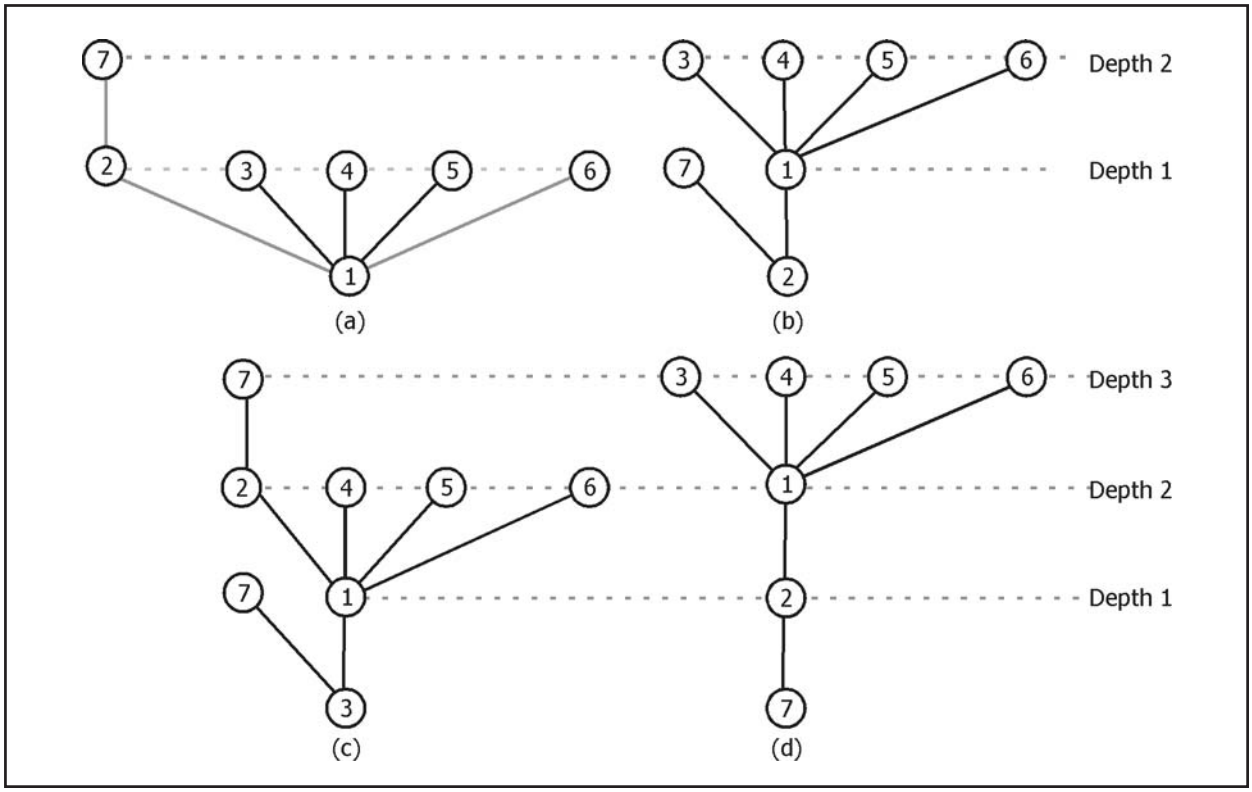


Fig. 1c. Using this intrinsic notion of space topology, space syntax quantifies the accessibility measures of settlement roads.

3. COMPUTATION OF ACCESSIBILITY WITH GRAPH THEORY

Space syntax describes the topological connections of unit spaces through depth analysis typically using the graph theory. Fig. 2 describes the justified graphs of four axial lines, distinguishing their network topology from one another.

Fig. 2 Justified Graphs. The Graphs are Drawn from Axial Lines 1, 2, 3, and 7 of Fig. 1c. Line 1, the Base Line in Fig. 2a, has the Direct Connections to Five Other Lines (lines 2 to 6) and an Indirect Connection to Line 7 (via line 2); so on and so forth.



In space syntax, the direct connections of unit spaces are known as connectivity (Hillier *et al*, 1984) or connections at depth 1, and the strength of this connection gets weakened, in terms of accessibility, when the units become distantly connected from the base unit. As an example, line 1, the base unit in the graph of Fig. 2a, has most of the connections at a lower depth than others, suggesting that line 1 is closely accessible from other lines in the entire system. However, in space syntax, this notion of close accessibility is further detailed out through a depth-wise connection analysis, commonly known as mean-depth analysis (Hillier *et al*, 1984).

3.1 Mean Depth

The mean depth of a unit space is the number of unit (s) that a trip-maker on average needs to cross from one unit to reach all other units in a system (Hillier *et al*, 1984). In a justified graph, the value of a specific depth denotes the number of units the trip-maker needs to cross to reach all units of that depth. For example, in Fig. 4.1d, the trip-maker needs to cross one line to reach line 2 because line 2 belongs to depth 1. Similarly, in the same graph, the trip-maker needs to cross three lines to reach each of the lines (lines 3 to 6) at depth 3. Using this process of quantification of unit connections, space syntax determines how one unit space, on average, is connected to all other units (equation 1).

$$\underline{D} = \frac{\sum d.n}{k-1} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

Where,

$\underline{D}$ = mean depth

d = depth (1, 2, 3, … etc.)

n = number of unit spaces at a specific depth

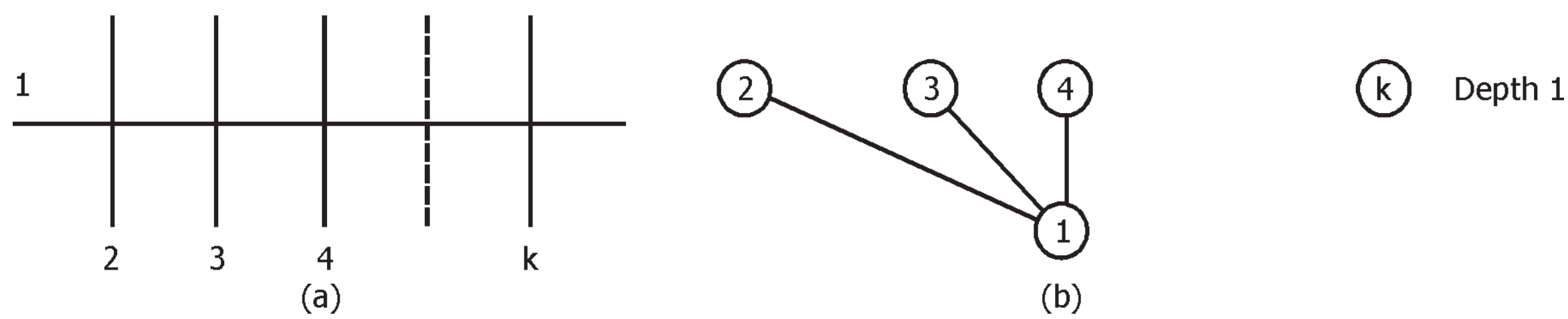
k = total unit spaces that comprise the system

Moreover, along with the mean depth parameter, the composition and size (*k* value) of a system, analyzed next, also influence accessibility measures of unit spaces.

3.2 System Composition: Relative Asymmetry

The previous discussion has pointed out that locations of certain unit spaces within a specified system make them more closely accessible than others. The lower the measure of the mean depth of a unit, the more closely accessible the unit is. Hence, the measure of mean depth is a relative parameter in terms of how the unit is located in the system, and because of this relative measure, the mean-depth measure of a unit space of a specified system cannot be compared with the others' unless they all are assessed on a common scale. In space syntax, this scale is known as scale of symmetricity (Hillier *et al*, 1984).

Fig. 3 Lowest Mean Depth.(a) Axial Map. (b) Justified Graph of Axial Line 1.



This is because, within a specified system, the mean depth measure of a unit space gets reduced when the layout itself tends to become a symmetric layout, and vice versa.

Space syntax defines the scale of symmetricity with the lowest and highest measures of mean depth, and the relative measure of a mean depth (of a unit space) within these limits represents how symmetrically the unit is connected to all other units. The lower limit of the scale of symmetricity is the lowest measure of mean depth of a unit space (or an axial line) regardless of its system definition. Theoretically, this measure becomes lowest when it provides direct connections to all other units of the system (see Fig. 3). In this case, one needs to cross only one unit to reach any other unit.

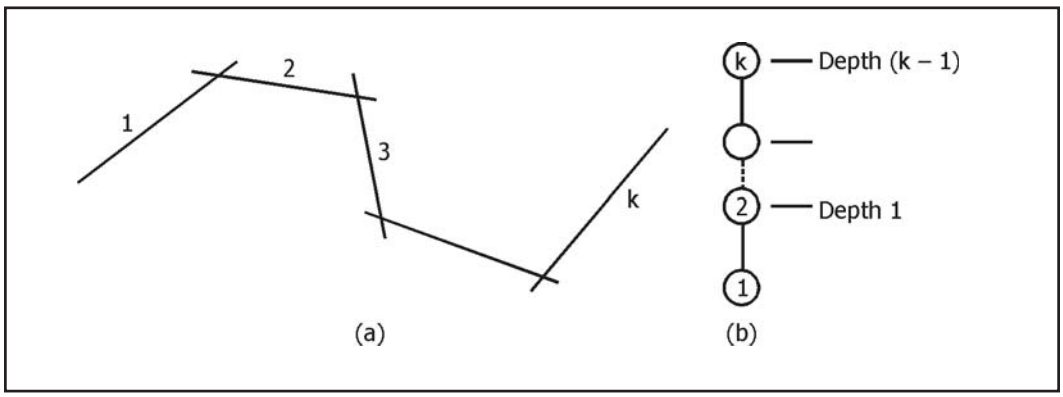
Fig. 3a describes a system of *k* number of axial lines, and here, line 1 (the base unit in the graph) is directly connected to all other lines; that is, a trip-maker, starting from line 1, only needs to cross one unit to reach any other unit. Therefore, the lowest value of mean depth is 1, and this lowest value can also be derived using equation 1.

$$D\ (\text{lowest}) = \frac{1\ (k-1)}{k-1} = 1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (2)$$

Similarly, the upper limit of the scale is the highest mean-depth measure of a unit space, and theoretically, this measure becomes highest when a trip-maker needs to travel the longest topological-distance to reach the destination (see Fig. 4).

Fig. 4a describes a system of *k* number of axial lines, in which all units are serially connected to each other. This composition develops the longest topological-distance between the first and the last units. In this situation, a trip-maker, starting from line 1, needs to cross all lines to reach line *k* (the last one). Again, using equation 1, highest measure of mean depth is determined *k*/2.

Fig. 4 Highest Mean Depth. (a) Axial Map. (b) Justified Graph of Axial Line 1.



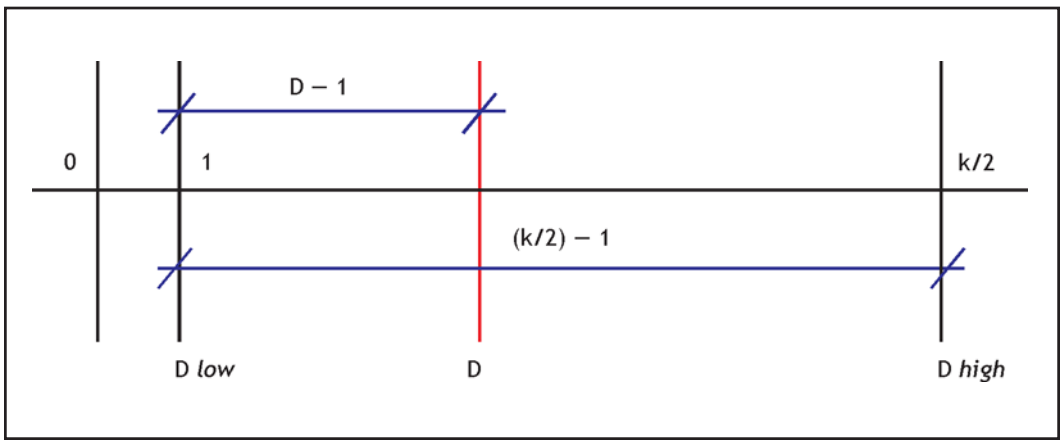
$$D\ (highest) = \frac{1(1) + 2(1) + 3(1) + \ldots\ldots\ldots\ldots + (k-1)\ (1)}{k-1} = \frac{k}{2} \quad \ldots\ldots\ldots\ldots\ldots\ (3)$$

The above analyses show that the measure of mean depth of any unit space in any system cannot be smaller than 1 and larger than $k/2$, where k is the total number of unit spaces of the system. Using these two limits, the scale of symmetricity is defined (Fig. 5).

The scale of symmetricity determines the relative measure of a mean depth (D), and it is the increment (in terms of depths) from the lowest measure with respect to the range of the scale. When the actual mean depth of a unit is D, the increment becomes D – 1 with the range of $(k/2) - 1$. In space syntax, the relative measure of a mean depth is termed relative asymmetry or RA, and it is calculated using equation 4.

$$RA = \frac{D-1}{(k\ /\ 2\ ) - 1} = \frac{2(D-1)}{k-2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (4)$$

Fig. 5 Scale of Symmetricity.



The relative asymmetry of a unit space describes the influence of system composition (symmetric or asymmetric) on the accessibility measures of its unit spaces quantifying how symmetrically each unit is connected to the other units within the range of symmetricity that the composition could provide.

3.3 System Size: Real Relative Asymmetry

Along with the system composition, the size of a system (or *k* value) also influences accessibility measures of the unit spaces. That is, relative asymmetries (of unit spaces) of two different systems cannot be compared on the same scale unless both systems are made of an equal number of units regardless of their individual compositions. Therefore, in order to develop a generalized formula for determining accessibility, it is also important to consider the system size. This measure of accessibility, in space syntax, is known as real relative asymmetry or RRA. The real relative asymmetry of a unit space is the ratio between its relative asymmetry and a factor (commonly expressed with Dk factor) that distinguishes the systems based on their sizes (or *k* values).

One way to determine this factor is to assume that, when the size of a system increases, the justified graph of each unit space tends to become more like a diamond shape (or a ring shape). This phenomenon is measured by Dk value of a specified system, and it is calculated by equation 5 (Hillier *et al*, 1984).

$$D_k = \frac{2[k\{\log_2((k+2)/3) - 1\} + 1]}{(k-1)(k-2)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

And

$$RRA = \frac{RA}{D_k} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

3.4 Integration

Previous discussion has shown that a lower measure of mean depth makes a unit space more closely accessible from all other units, whereas a higher measure makes the unit distantly accessible. This notion of mean depth becomes more comprehensive when two other spatial parameters system composition and system size are considered and described through the notion of real relative asymmetry or RRA.

The integration of a unit space is its reciprocal of RRA, and it describes how closely (or distantly) the unit is topologically accessible from all other units within a given system addressing its symmetricity and size. The map that distinguishes unit spaces based on their integrations is the integration map. Fig. 6 shows examples of the mean depth integration maps of the roadway structure shown in Fig. 1, and Table 1 reports the accessibility measures.

Fig. 6 Axial Analysis. (a) Mean Depth map. (b) Integration Map. Mean-depth and Integration Measures Reduce as the Color of the Lines Changes from Red to Blue.

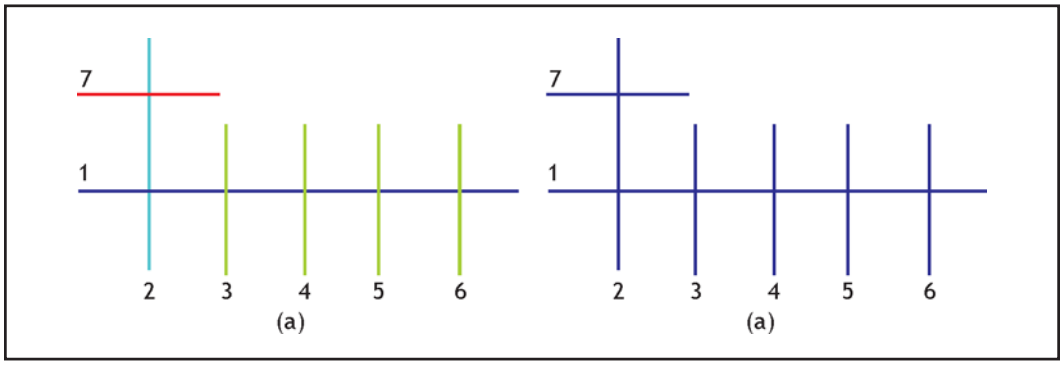


Table 1 Space Syntax Analysis Results.

	(1)	(2)	(3)
Line #	Connectivity	Mean depth	Integration
1	5	1.16667	5.094740
2	2	1.66667	1.273680
3	1	2.00000	0.849123
4	1	2.00000	0.849123
5	1	2.00000	0.849123
6	1	2.00000	0.849123
7	1	2.50000	0.566082

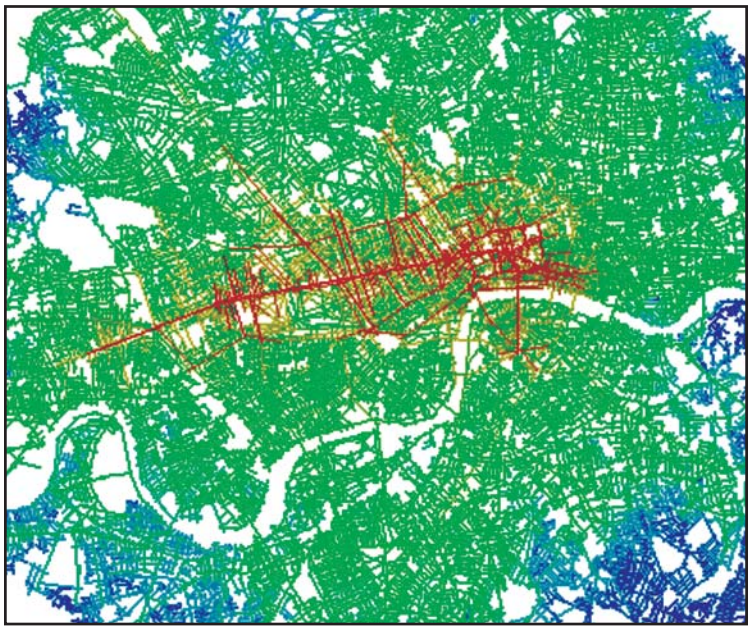
4. GLOBAL AND LOCAL INTEGRATIONS

In the previous discussion, integration of unit spaces (or axial lines) have been determined with an understanding as to how closely or distantly each unit is accessible from all other units of a system. This integration analysis is also known as the global-integration analysis or integration radius-n analysis. However, an analysis can also be restricted at a lower depth of connectivity to determine the accessibility of the units at the local or neighboring level (Hillier *et al*, 1984). For example, in an integration radius-3 analysis, only the units that are three depths away are considered in order to determine local integrations describing how each unit is accessible from all other units that fall within the restricted radius boundary (radius-3 in this case). Similarly, in the integration radius-2 analysis, space syntax will only take into account line connections that are two depths away from the base unit.

5. APPLICATION OF SPACE SYNTAX IN TRAFFIC ESTIMATION

Typically, space syntax determines accessibility measures of settlement roads through the concept of integration. The higher the value of integration of an axial line or a road segment, the greater is its accessibility from all other

Fig. 7 Axial Analysis of Central London (Hillier 1998). Integration of the Lines Reduces as their Color Changes from Red to Blue.



segments. In reality, it has also been found in many cases that the integration results of road segments are positively correlated to their actual traffic volumes (Penn *et al*, 1998; Hillier *et al*, 1987; Caria *et al*, 2003). In an axial analysis of the major thoroughfares of Central London (see Fig. 7), Oxford Street, which happens to be the main shopping street (the busiest in Europe) in Central London, was found to be the most integrated street in the system (Hillier, 1998).

In a more detailed study of Central London (Hillier, 1998), very high traffic correlations (pedestrian) were obtained. At Baltic House Area, the correlation (r-squared) went up to 0.773 (at $p < 0.05$). At the 477 observed locations of Bransbury, South Bank, Calthorpe Street, and South Kensington in Central London the combined r-squared was reported 0.68 (Penn *et al*, 1998). The study also suggested a significant increase in the correlations (r-squared went up to 0.84) when the traffic flows were used with respect to the net road with (without parking areas). Traffic correlation studies of other areas of London are reported in Table 2.

Table 2 Traffic Correlation Results

Areas	r-value
Barnsbury	0.80
St. Peter's Street, City of London, High gate	0.75 (avg.)
Islington	0.73
Golders Green (suburban area)	0.80

In a study of 16 areas in Santiago, the traffic correlation (r-squared) for spatial configuration alone was found to be 0.54 for 212 locations without taking the net road width into account (Hillier et al. 1987). In another extended study in

Table 3 Correlations Between Integration Results and Pedestrian Movement

Time Periods Breakdown			r-squared
Integration-n	Morning (8.00h to 12.00h)	Entire area	0.44
Integration-5			0.48
Integration-n	Lunch time (12.00h to 14.00h)	Entire area	0.58
Integration-5			0.58
Integration-n	After noon (14.00h to 20.00h)	Entire area	0.62
Integration-5			0.67

Table 4 Correlation Between Integration-n and Movement Rates

Pedestrian		Vehicular	
Category	r-value	Category	r-value
All Pedestrian	0.46	All vehicle	0.74
Adults	0.57	ATC	0.77
Children	0.26	Car/Truck	0.59

Lisbon (Caria e al. 2003), the pedestrian movement of Avenidas Novas was correlated to the axial integration results (local and global). The study was done at different times of a day. Positive correlations were found in every case (Table 3). The high and positive correlations between integrations and movements, pedestrian and vehicular were also found in two the arctic communities in North Canada studied (Dawson, 2003). The correlations are reported in Table.4.

All these traffic correlation studies suggest that space syntax has the ability to capture the trends of movement of settlement roads through their accessibility measures or integrations. The higher the correlation (r), the greater the predictive accuracy of the traffic estimates. Furthermore, it has also been found that the measure of global integration is predominantly positively correlated to the vehicular traffic, whereas the measure of local integration has the higher predictive accuracy for the pedestrian traffic. However, the space syntax community has come up with other definitions of the unit spaces, which also seem to be promising in the area of traffic assignment.

6. CONCLUSIONS

The primary input of the equilibrium approach to traffic estimation is the origin-destination (OD) trip-data, and these are typically surveyed. Furthermore, these surveys are required to be performed on a regular basis to determine the changes in the OD trips due to new developments and renewals. These surveys are not only cost intensive and time consuming, but they can only be used for the development of short term transportation strategies (Reddy *et al*, 1998; Penn *et al*, 1998).

This article has shown how space syntax researchers have developed an alternative model for traffic assignment by analyzing the accessibility measures of settlement roads. This evidence based approach to traffic assignments assists planners in determining the level of service of the city roads with the volume to capacity ratio, and thus facilitates in making effective transportation policies that help to reduce traffic delays, enhance transportation safety, increase the value of transportation assets, and expand economic opportunity in terms infrastructure developments of the city. As the space syntax model does not require rigorous trip-surveys, this approach is more appropriate for traffic

estimation than the classical models for the growth and redevelopment of the densely-populated cities of India where the absence of OD trip-data often poses problems in calibrating and applying the classical models for movement network modeling.

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