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Unit-segment Analysis: A Space Syntax Approach to Capturing Vehicular Travel Behavior Emulating Configurational Properties of Roadway Structures

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One of the critical concerns of axial analysis, a space syntax approach to capturing vehicular travel behavior emulating configurational properties of roadway structures, is the absence of the time-cost consideration while dealing with route-choice problems encountered in grid-like urban textures. This study shows that the time-cost parameter of travel can also be introduced into the syntax approach to capturing the route-choice decisions for the purpose of modeling vehicular movement networks with greater accuracy. Assuming that roadway units are trip-origins and trip-destinations and that they also act as connecting route segments among each other, a theoretical foundation has been proposed showing how the mobility characteristics of these units, in terms of the time-cost of travel, influence their accessibility measures or syntax integrations. These new roadway units are the unit segments, and their integrations are found to be better indicators of vehicular trip-makers' route-choice decisions than axial integrations. Conclusions suggest that the unit-segment analysis of an urban grid captures the general behavior of vehicular flow by substantiating the fact that trip-makers tend to pick a specific set of roadway units that not only comprise the close connection between a trip-origin and a trip-destination but also consume less time for travel.

Keywords: space syntax; vehicular traffic assignment; travel times; mobility characteristics; unit-segment analysis; axial analysis

1. Introduction

Apart from the cost and time involved in collecting origin-destination trip-data, needed for calibrating and applying the classical models for traffic assignment (Penn, Hillier, Banister, and Xu, 1998), the homogeneity of these data occasionally becomes contentious (Paul 2011a) because of mixed land-use patterns and mixed traffic systems of settlements. As a result, transportation policies developed with traffic predictions derived from these trip-data occasionally turn out to be less effective when implemented for urban infrastructure developments resulting in traffic congestion,

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unsafe commutation, an inability in making quick traffic management action plans during emergencies, and all these together, a less-effective utilization of transportation investments.

An alternative to the classical theories of traffic assignment is space syntax (Hillier and Hanson, 1984). Studies suggest that, along with other applications, space syntax has the ability in capturing the trends of vehicular travel demands merely by analyzing roadway accessibility embedded in urban morphology (Penn et al. 1998; Karimi and Mohamed 2003; Dawson, 2003, and many others). Traditionally, by applying the longest and fewest lines, or axial lines (Hillier et al. 1984), space syntax quantifies the topological relationships (that is, nonmetric) of roadway units and describes these relationships of connectivity predominantly through a configurational measure called integration (Hillier, 1999). As identified by many syntax researchers, the measure of integration itself accounts for the majority of the variance in flows from street to street (Penn et al. 1998; Hillier, Penn, Hanson, Grajewski, and Xu, 1993; Hillier, 1999). However, simplistic as the axial-line approach to capturing the traffic-flow trends is, there are areas in which the model appears to have critical limitations (Hillier et al. 1993; Hillier, 1999; Ratti 2004; Eisenberg, 2005). One such limitation, as identified by Hillier et al. (1993, page 30), is that axial integrations becomes less deterministic in predicting movement while dealing with route-choice problems encountered in grid-like urban textures. By using an ideal regular grid, Ratti (2004, page 497) has theoretically proven that all axial lines in the grid yield equal integrations implying, which is fair to say an unrealistic outcome, that all the lines of the grid are expected to receive equal or equivalent traffic flows.

The philosophy behind the development of the axial-line theory is grounded in the assumption that trip-makers tend to reduce the number of turns—also understood as the topological distance between each pair of lines in a specified network (Ratti 2004, page 488)—while selecting their routes as opposed to reducing the time-cost of travel typically considered in the classical traffic-assignment models. Now, if we assume that a trip-maker's notion of movement, as pointed out by Penn (2003, page 31), is "the average number of changes of direction encountered on routes, not to specific destinations, but to all possible destinations," the only possible representation of a specified roadway structure is the minimal set of longest and fewest accessible lines that pass through the connecting roadway segments. Each line here is an axial line. Space syntax, in this context, finds out which of these lines are likely to receive more trips than the rest using their integration measures.

From the vehicular trip-making point of view, however, this axial notion of route choice is inadequate simply because the mobility characteristics of all roadway units (or axial lines) in a given structure, that, along with the distance parameter, also influence the time-costs of travel and, thus, affect the trip-makers' route-choice decisions, cannot be presumed equal or equivalent. Apart from flow congestion, vehicular travel speed changes mainly because of speed zoning, roadway geometry, traffic rules, and other localized roadway conditions and events. Therefore, it does not seem reasonable to buy the idea that vehicular trip-makers (not pedestrians) will always tend to pick a route that is comprised by the least number of roadway units, as space syntax suggests (see Hillier et al. 1984; Hillier, 1999; Penn et al. 1998), even if the route requires a higher travel time than an alternative route with a lower travel time. In other words, because the mobility characteristics of roadway units are usually not found to be equal in real conditions, it is quite possible that trip-makers will tend to pick routes that will not only provide closer connections to their destinations but will also allow them to navigate grids with higher speeds reducing the overall time-costs of travel. Therefore, a clear understanding of this awareness through the syntax representations of roadway units might explain how the configurational measures of these units can be used to envisage a realistic pattern of urban vehicular flow. Assuming that these roadway units are trip-origins and trip-destinations (Paul, 2011b) and that they also act as connecting route segments among each other, this study aims to show that the mobility characteristics of these units, in terms of the time-cost of travel, influence their accessibility measures or syntax integrations and, thus, affect their flow demands. The study is divided into four parts. First, the role of the axial-line approach to modeling a vehicular movement network is described, and then its deficiencies are examined precisely from the route-choice point of view. Second, a thorough review on the movement-space relationship is discussed showing how the time-cost parameter of travel influences the vehicular trip-makers' route-choice decisions. The discussion develops the concept of unit segment and proposes that, while dealing with route-choice problems encountered in grid-like roadway structures, unit-segment analysis is a better approach towards modeling vehicular movement networks than axial analysis. Third, statistical evidences are produced, that develop a comparative assessment between the traffic-assignment accuracies produced by both the analyses, and the hypothesis is tested. Finally, the findings are summarized, and the conclusions are drawn.

2. Role of axial line in modeling vehicular movement networks

Let us begin by quoting Hillier (1999, page 169; also appeared in Ratti, 2004):

> "In the study of cities, one representation and one type of measure has proved more consistently fruitful than others: the representation of urban space as matrix of the longest and fewest lines, the axial map, and the analysis of this by translating the line matrix into a graph, and use of the various versions of the topological (that is, nonmetric) measure of patterns of line connectivity called integration."

Studies show that the axial-line unit has predominantly been applied in determining roadway integrations especially for the purpose of modeling movement networks (Penn et al. 1998; Hillier, 1999; Dawson, 2003; Peponis, Ross, and Rashid, 1997; Karimi et al. 2003; and many others). The reason behind this application is the syntax argument that the trip-maker's notion of movement is the average number of changes of direction encountered on routes, not to specific destinations, but to all possible destinations (Penn, 2003). With this understanding, space syntax suggests that the only possible representation of a roadway structure is the minimal set of longest and fewest lines (refer to Figure 1), axial lines, that pass through the connecting roadway segments.

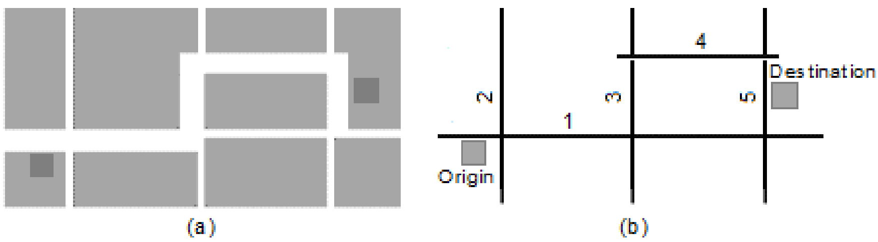

Figure 1. Development of axial lines. (a) Roadway structure; land-use and building blocks are shaded. (b) Axial map.

In Figure 1, as an example, five axial lines are generated from within a hypothetical roadway structure. Each line here is presumed to reflect the trip-maker's awareness of the shortest topological travel distance among each other. That is, starting from line 1, a trip-maker can directly access three lines: 2, 3, and 5. Similarly, starting from line 2, the trip-maker at least has to use line 1 to reach line 3 or line 5. And so on. Using justified graphs, shown in Figure 2, the topological relationships of line 1 and line 2 with all other lines are further elaborated. Each line in the graph is plotted in accordance with the degree of depth, that is, how many changes of direction separate the line from the starting line, and according to Ratti (2004, page 488), the significance of depth here can be referred to as "a kind of distance: it represents the minimum number of changes of direction to go from the origin to any other segment in the network."

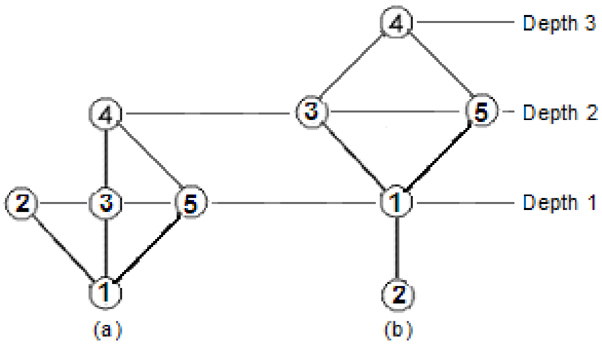

Figure 2. Justified graphs. (a) Axial line 1. (b) Axial line 2.

The graphs in Figure 2 show that most of the axial lines are connected to line 1 at lower depths than line 2. This means that, because line 1 is more closely accessible from all other lines than line 2, in terms of depths, the average topological trip-distance to reach line 1 from each of the other lines is shorter than that of line 2. Now, if we assume that the perception of distance itself plays the key role in influencing the trip-makers to make a rational choice of route, then line 1 will be the most rational choice, and consequently, line 1 will have a greater ability in receiving trips than line 2. From the syntax analysis stance, line 1 will also yield higher integration conforming to the average topological distances as opposed to line 2. This way, the competency of receiving trips of each line in the structure can be compared with one another through the measure of integration.

On the other hand, the classical traffic-assignments models sketch a different picture on the trip-makers' common awareness of route choice. Apart from the distance parameter, in metric or even topological terms, the understanding of closeness between a trip-origin and a trip-destination also counts on the parameter of travel speed (Fricker and Whitford, 2005). That is to say, traveling at a higher speed, from the cognitive perspective, brings the trip-destination closer to the trip-origin by reducing the time-cost of travel and, accordingly, influences the trip-makers' route-choice decisions. In space syntax, this understanding of time-cost has not been considered while developing the axial-line concept, and perhaps for this reason, vehicular flow predictions produced by some axial analyses have occasionally turned out to be not so accurate (Peponis et al. 1997).

However, critical as the reasoning of route-choice decisions in vehicular trip-making is, the above review frames out a fascinating question in space syntax transportation research: Can space syntax make more realistic and, thus, accurate vehicular flow predictions than its traditional axial model by considering the time-cost parameter of travel in its analysis? This leads to explore further the movement-space relationship that might throw a deeper insight into how vehicular travel behavior emulates configurational properties of roadway structures.

3. Movement-space relationships

In the classical traffic-assignment models, movement is understood through origin-destination trips: commonly known as OD trips. These trips are related to settlement spaces in two ways: (1) through traffic-analysis zones — trip-origins and trip-destinations that generate trips; (2) through OD routes — roadway channels that carry the generated trips. In space syntax, on the contrary, movement is typically understood through the measure of integration. That is, the higher the integration a roadway unit yields, the greater the potency of receiving trips the unit gains. In both the theories, however, settlement spaces are understood as channels of movement. In syntax literature, these channels are the roadway units; whereas in the traffic-assignment models, they are the OD routes. The only difference is that space syntax does not distinguish roadway units based on their ability in generating trips, or perhaps, it has been assumed in the basic premise of a syntax analysis that all its roadway analysis units have equal or a unit ability to generate trips (Penn and Turner, 2003). This understanding of the movement-space relationship develops two key insights of this study. First, in a syntax integration analysis, can we not consider the roadway units equivalent to the sources of trip-generation, that is, trip-origins and trip-destinations, (also see Paul, 2011b, for further explanation of this rationale)? And second, the notion of route competency, as described in the classical traffic-assignment models, must have a comparable meaning with the notion of route accessibility as understood in the syntax theory.

4. Route competency vs. route accessibility

Route competency, in the classical traffic-assignment models, is considered a measure of route choice that distinguishes roadway units based on their ability in receiving trips (Fricker et al. 2005). The higher the competency, the greater the traffic expected. The time-cost parameter of travel here plays the key role in evaluating which set of roadway units comprising a trip-route is more competent than the others. In space syntax, on the other hand, the competency of a specific roadway unit is judged by its measure of accessibility or, traditionally, by the unit's integration measure. And as pointed out before, the higher the integration a roadway unit yields, the greater the ability in receiving trips the unit gains. Therefore, the perceptions of route competency and route accessibility appear to explain the fact that they individually represent a common ground while describing the trip-makers' general awareness of route choice. This common ground has further been substantiated in Figure 3 by interpreting the concept of route competency through the notion of roadway accessibility.

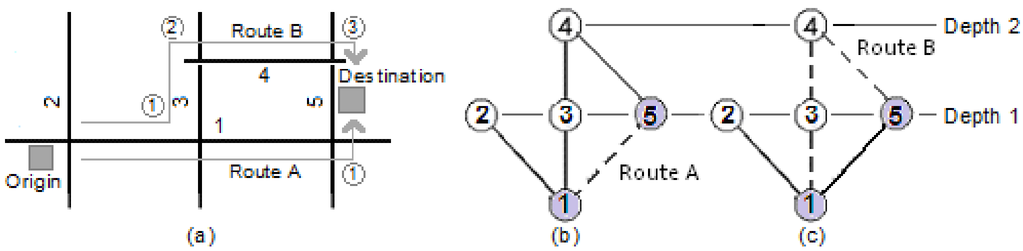

Figure 3. Representation of OD routes through justified graphs (source: Paul, 2009). (a) Routes A and B; the number of roadway units travelled in each route are circled. (b) and (c) are justified graphs showing two possible topological routes between line 1 and line 5. (b) Route A: the shortest topological route. (c) Route B: the longest topological route.

Imagine line 1 and line 5 in Figure 3(a) act as a trip-origin and a trip-destination, respectively, and route A and route B connect them. In this scenario, and form the classical traffic-assignment stance, the competency of these two routes will be judged by their individual travel times. Now, if we assume that there is no traffic congestion, the travel times of these routes can be simplified down to the ratios of their individual metric lengths and travel speeds. Furthermore, if we also assume that both the routes have equal mobility characteristics (say residential streets) and that the trip-makers' general perception of distance is unit[2] instead of metric (Hillier and Iida, 2005), then route A will be considered more competent in receiving trips than route B. This is because, in route A, a trip-maker will need to travel only one unit to reach the destination (or line 5); whereas in route B, as many as three units will need to be travelled.[3]

In space syntax, route A will always be considered more accessible or competent than route B, as in the former case, the destination is fewer number of depth(s) away than the latter [refer to Figures 3(b) and 3(c); routes are shown in broken lines]. This is because the fundamental presumption of an axial analysis is that trip-makers always tend to pick the shortest connections regardless of the route speeds. Therefore, the notions of route competency and route accessibility can be considered analogous to one another when the mobility characteristics of all possible routes between a trip-origin and a trip-destination are considered equal and when the trip-makers' common notion of distance is perceived as unit instead of metric. This theoretical argument of route accessibility formulates a new definition of roadway analysis unit, unit segment, for modeling vehicular movement networks with space syntax.

5. Unit segment: a new definition of roadway unit

Much of the discussion presented in the previous sections underlines the argument that, in vehicular trip-making, axial integrations are somewhat inadequate to be considered good indicators of route-choice decisions. Rather, from the classical traffic-assignment stance, it appears to be more reasonable to accept the notion that, while predicting vehicular flows through syntax configurational measures, the roadway units need to be distinguished by their time-costs of travel (Fricker et al. 2005), particularly for the cases, in which the problem of route choice arises. In order to describe the time-cost of travel through roadway units, the concept of unit segment is proposed. Assuming that the trip-makers' notion of distance is unit instead of metric and that trip-makers face no traffic congestion, as seen in the AON model (Fricker et al. 2005), unit segments are the roadway units that are distinguished by their mobility characteristics. That is, in a unit-segment analysis, an artery is considered to have the greater potency of attracting trips than a residential street when they both comprise equal units of distances or depths (refer to Figure 2 for the explanation depth) while connecting a specific trip-origin and a specific trip-destination. Based on this theoretical reasoning, the hypothesis of this study is developed. That is, in vehicular trip-making, unit-segment integrations are expected to be better indicators of route-choice decisions and, thus, better predictors of movements than axial integrations.

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[2] According to Hillier et al. (2005, pages 553-4): "… in recent years, research results have accumulated in cognitive science, which suggest that the metric distance assumption is unrealistic, not perhaps because we do not seek to minimize travel distance, but because our notions of distance are compromised by the visual, geometrical, and topological properties of networks."

[3] Contradictory results may, however, be obtained if the mobility characteristic of route B becomes significantly higher than that of route A or if route A turns out to be considerably lengthier, in metric terms, than route B.

However, in order to appropriately test this hypothesis, a few working conditions are suggested. First, as pointed out before, axial integrations becomes less deterministic in predicting traffic flows while dealing with route-choice problems encountered in grid-like roadway structures. Consequently, in some cases, the flow predictions produced by an axial analysis may turn out to be less accurate. Therefore, the fair way to evaluate whether a unit-segment analysis is a better approach to modeling vehicular movement networks than an axial analysis is to take on a study methodology that compares the accuracies of the flow predictions, generated by both the analyses, using a common grid-like roadway structure. Second, unit segments, by definition, need to be distinguished by their mobility characteristics while dealing with route-choice problems. Therefore, while developing a unit-segment map, all roads of the structure need to show a distinct roadway hierarchy. Finally, because the theory of unit-segment analysis, at this preliminary stage of development, does not take the land-use parameter into account, it is recommended selecting an analysis area where the variations of land-use typology and density are minimal. This way, the discrepancies in travel behavior on account of diverse land-use types and densities can be lessened and maximum accuracies in the analyses results can be obtained.

6. Methodology

Tech Terrace, a small residential neighborhood located at the center of Lubbock (Figure 4), a typical North American city in West Texas, has appeared to be the appropriate analysis area for the case study because of its grid-like roadway structure, distinct roadway hierarchy: all residential streets of the neighborhood are confined by the peripheral arteries, and evenly distributed land uses: mostly single-storied detached houses. The axial map of Tech Terrace is developed by identifying the minimal set of longest and fewest accessible lines representing the roadway structure of the neighborhood; whereas its unit-segments map (let us call it type 1 unit-segment map) is drawn by distinguishing the roadway units in accordance with their mobility characteristics: arteries with a speed range of 40-45 mph and residential streets with a speed range of 20-30 mph. Then integration analyses are performed for both the maps using Depthmap (Turner, 2001-06).

Interestingly however, as observed onsite, not all the internal residential streets of Tech Terrace show similar flow characteristics of vehicular traffic, even though they are categorized to have equal mobility characteristics. The flows of some of these streets get interrupted when they face stop or yield signs, and as a result, their actual mobility characteristics reduce. Therefore, it is also fair to speculate that these residential streets might be lesser considered for travel than ones which do not face such signs. In order to verify, if the local traffic rules influence the mobility characteristics of the roadway units, and thus, affect their travel demands, the internal streets of the neighborhood are further distinguished based on how they face the stop or yield signs [Figure 5(d)], and a second map, type 2 unit-segment map, is drawn. In type 2 unit-segment map, a unit segment, depicting a residential street, further splits into two units (but remains connected with one other) at the roadway intersection, where the street faces the stop or yield sign. Then, again, an integration analysis is performed for type 2 unit-segment map. All integration maps are given in Figure 5.

Vehicular flows, morning and evening peaks, are counted in fifteen-minute slots at seven randomly selected roadway intersections (circled in Figure 4) located on the arteries and on the residential streets of the neighborhood. These counts comprise left turns, right turns, and through traffic in all four directions of each adjoining intersection. Vehicular flows of roadway units representing axial lines and unit segments of all three maps are then calculated by identifying their outgoing and incoming flows through the corresponding intersections. The outgoing flow of a roadway unit is its downstream flow; whereas the incoming flow comprises the selected turns and the through traffic that enter into the unit from the adjoining ones. Finally, the integration results of these units obtained from all three analyses are correlated with their corresponding vehicular flows. The correlation results are reported in Table 2.

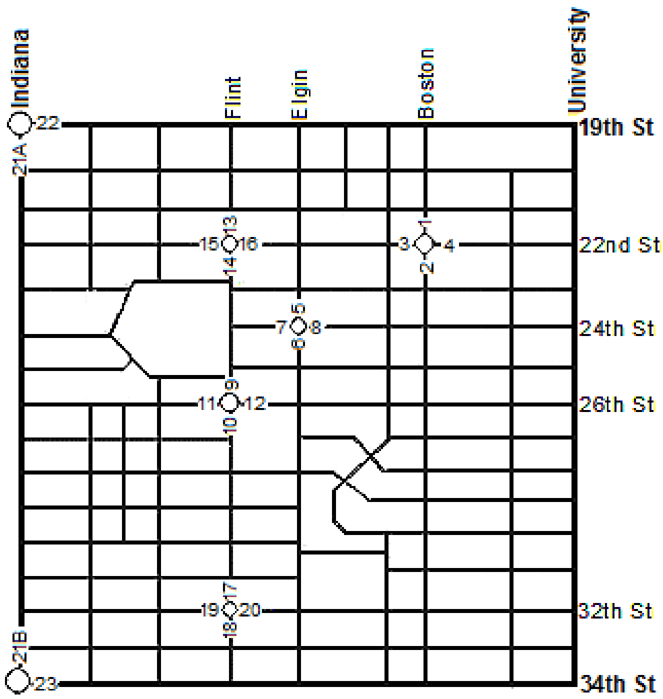


Figure 4. Tech Terrace, Lubbock, Texas (source: Paul, 2009). The traffic counts of the selected roadway units (numbered in the map) are reported in Table 1.

Table 1. Traffic counts

ID	Name	slot 1	slot 2	vph	ID	Name	slot 1	slot 2	vph
1	Boston	105	137	484	13	Flint	-	-	324
2	Boston	102	137	478	14	Flint	-	-	320
3	22nd St	32	16	96	15	22th St	-	-	71
4	22nd St	33	16	98	16	22th St	-	-	64
5	Elgin	10	10	40	17	Flint	-	-	252
6	Elgin	8	9	4	18	Flint	-	-	252
7	24th St	5	13	36	19	32th St	-	-	69
8	24th St	8	11	38	20	32th St	-	-	77
9	Flint	95	98	386	21A	Indiana	241	477	1,970
10	Flint	97	98	354	21B	Indiana	474	919	3,066
11	26th St	37	31	136	22	19th St	533	897	2,860
12	26th St	33	24	114	23	34th St	363	652	2,030

Note: Flow counts are as vehicle per hour (vph). Some of the figures have been obtained from the Traffic Engineering Department of City of Lubbock (source: Paul, 2009). Roadway units 21A through 23 are the arteries.

Table 2. Integration-movement correlations

		All-roads		Residential-streets	
Case	Analysis type	r	r-squared	r	r-squared
1	Axial analysis	0.17	0.03 (0.66)	0.48	0.23 (0.28)
	Unit-segment analyses				
2	Type 1 analysis	0.96	0.93	0.10	0.01 (0.67)
3	Type 2 analysis	0.70	0.49	0.82	0.67

Note: The all-roads category comprises the traffic counts of the arteries and the residential streets; whereas the residential-street category considers the counts of the residential streets alone; p-values are lesser than 0.01 unless mentioned in parentheses.

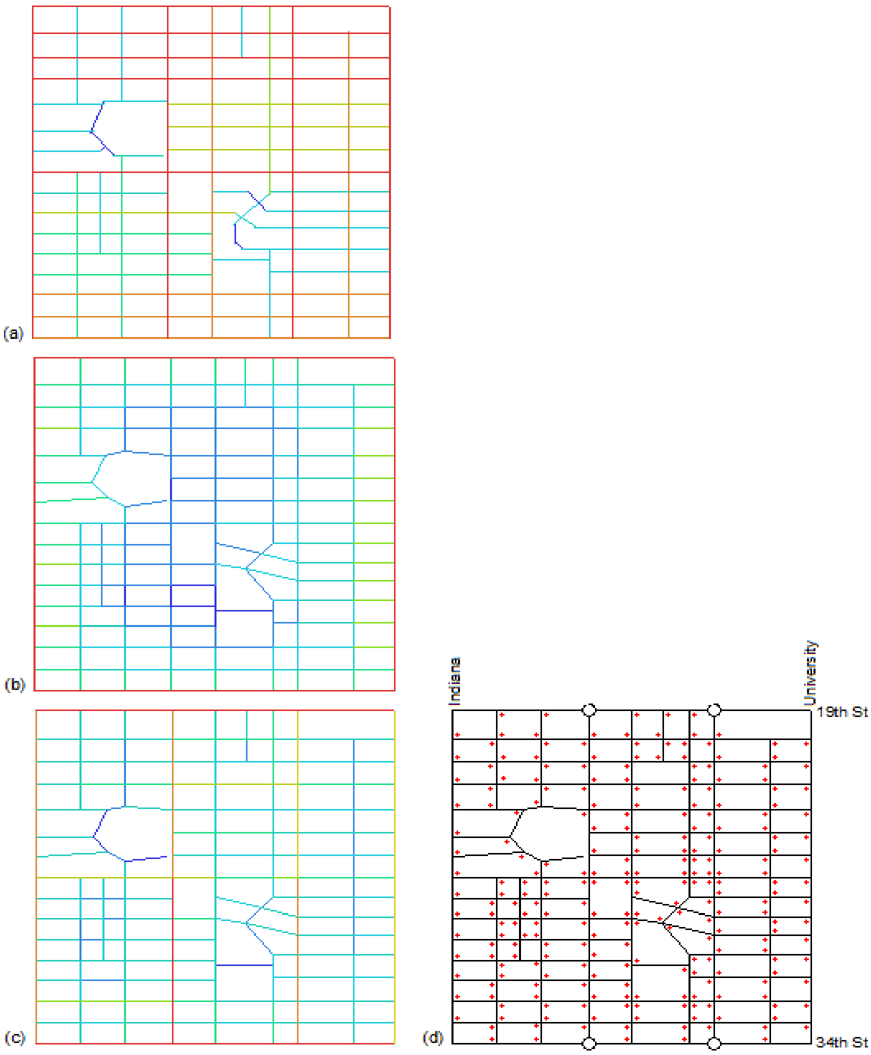
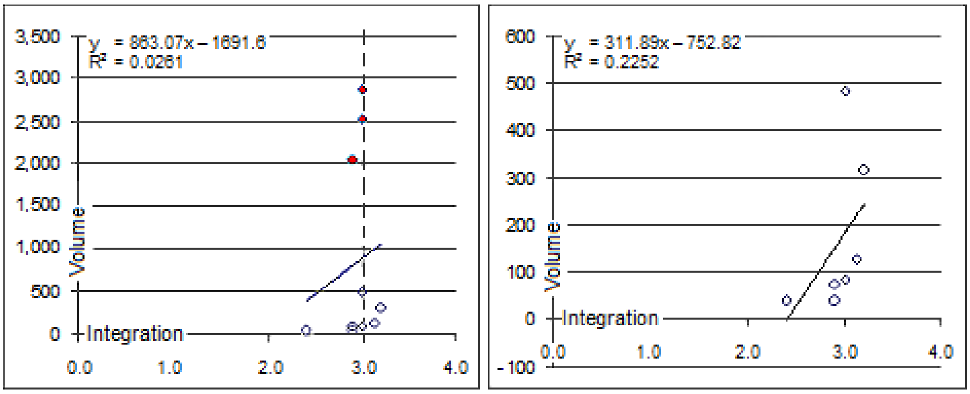


Figure 5. Integration maps of Tech Terrace (source: Paul, 2009); integration reduces as the color of the lines changes from red to blue. (a) Axial analysis, (b) type 1 unit-segment analysis, (c) type 2 unit-segment analysis, (d) locations of stop or yield signs.

7. Analysis and findings

7.1 Axial analysis

The scatterplots in Figure 6 illustrate the integration-movement relationships of the axial analysis of Tech Terrace. Almost no relationship ($r^2 \sim 0.03$) is found in the combined units of the arteries and the residential streets of the neighborhood. The scatter, however, develops two distinct outliers separating the arteries from the residential streets. Three solid dots, shown in Figure 6(a), represent the peripheral arteries; whereas the hollow ones are the residential streets. When the outlier of the arteries is removed from the scatter, the correlation is found to improve somewhat accounting for little over 20% of the variance in flows of the residential streets (refer to Table 2).



(a) (b)

Figure 6. Scatterplots: axial analysis. (a) All-roads. (b) Residential-streets.

Noticeably, the scatter of the all-roads category develops a paradox. Imagine a line [refer to Figure 6(a)] that distinguishes the relative positions of the solid dots amongst all hollow ones in terms of their integration measures. The line here clearly identifies that quite a few hollow dots have received higher integrations than the solid ones. Syntactically, this implies the fact that some of the residential streets of the neighborhood are expected to receive more trips than the arteries. In reality, however, the traffic counts of the arteries are found to be much higher averaging almost 2,500 vph than those of the residential streets averaging nearly 200 vph (see Table 1). This contradictory relationship between the two outliers substantially weakens the overall integration-movement relationship of the axial analysis of Tech Terrace.

As pointed out before, the traffic correlation of the axial analysis improves somewhat when the outlier of the arteries is removed from the scatter. One reason behind this development, from the syntax perspective, could be the greater accessibility of a few residential streets in comparison to the other residential streets. The integration map shown in Figure 5(a) verifies this observation and finds that the residential streets that run from one end of the roadway structure to the other (in both directions) turn out to be more integrated and, thus, have greater potency of receiving trips than ones that end well before the structure boundary.

The crucial finding of the axial correlation, however, is that the integrations of some residential streets are found to be higher than those of the peripheral arteries. This raises the key question of this study. That is, when the residential streets provide unobstructed accessibility from one end of the structure to the other (which is analogous to the peripheral arteries), and syntactically, when they are also more integrated than the arteries, why do the arteries still receive more trips than the residential streets in reality? There could be two possible explanations for this anomaly.

First, because the arteries are located at the periphery of the roadway structure, the axial analysis has identified them as segregated lines. Extension of the structure boundary might have made these lines relatively more integrated. The effect of the boundary consideration on the integration measure of a roadway unit is known as edge effect (Hillier et al. 1993; Penn et al. 1998). Because of the edge effect phenomenon, the measure of integration has occasionally been criticized while using it for developing configuration-movement relationships (Ratti, 2004; Penn et al. 1998). Second, as discussed before, it is quite possible that the trip-makers' common notion of route choice is influenced by the time-cost of travel. That is, vehicular trip-makers predominantly tend to pick roadway units that allow them to flow with higher speeds in order to reduce their overall time-costs of travel. In this situation, the average topological distance between one roadway unit and all other units in a given roadway structure needs to be understood through the notion of time-cost instead of the perception of distance alone. The notion of time-cost is simplicity itself. That is, starting from each roadway unit, how quickly, on average, the trip-makers can reach all other units. This provides the ground for the theory of unit-segment analysis, through which the time-cost parameter of travel has been introduced into the space syntax approach to modeling vehicular movement networks. The integration-movement relationships drawn from the two unit-segment analyses of the Tech Terrace network will show next how the time-cost parameter of travel, interpreted through the mobility characteristics of the neighborhood roads, influences the roadway integrations and affects their vehicular flows.

7.2 Type 1 unit-segment analysis

In type 1 unit-segment analysis, the roadway units of Tech Terrace have been distinguished by their mobility characteristics. The scatterplots shown in Figure 7 illustrate their configurational abilities to receive trips.

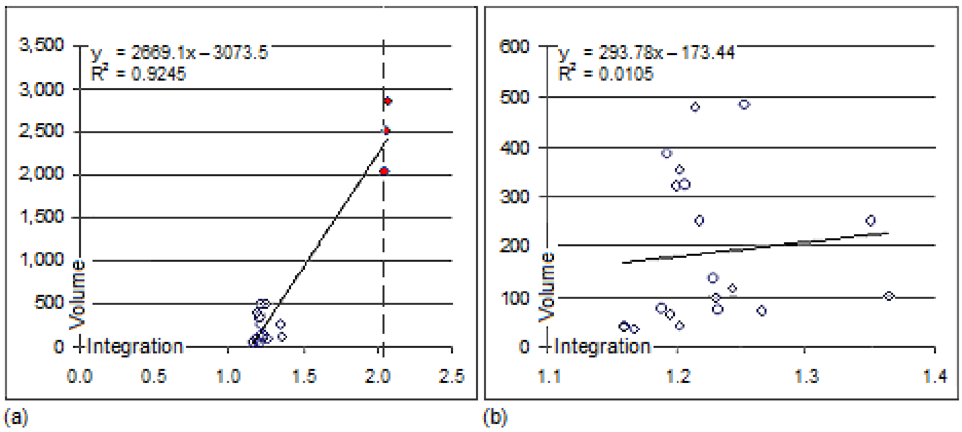


Figure 7. Scatterplots: type 1 unit-segment analysis. (a) All-roads. (b) Residential-streets.

The scatter of Figure 7(a) shows a significantly strong post-diction accounting for the majority of the variance ($r^2 \sim 0.9$) in flows of the arteries and the residential streets. The scatter again develops two outliers separating the arteries from the residential streets. The imaginary line here evidently supports the study proposition explaining that, because the arteries have high mobility characteristics, they are to yield high integrations and, thus, are expected to attract greater number of trips than the residential streets. However, the correlation drops radically (r = 0.10) when the outlier of the arteries is taken out from the scatter (see Table 2).

The strong traffic correlation of the unit-segment analysis, in summation, recognizes the fact that the arteries and the residential streets together have a strong ability in predicting vehicular flows of the neighborhood roads. That is, when the arteries and the residential streets are analyzed together, the arteries are always expected to yield higher integrations and, thus, to show stronger trip-attraction abilities than the residential streets, and vice versa. In order to cross-verify this finding, a hypothetical unit-segment map, in which an artery is purposefully placed at the center of the grid, is analyzed with an anticipation that the artery will still yield a higher integration than the surrounding residential streets. Figure 8 describes the scenario.

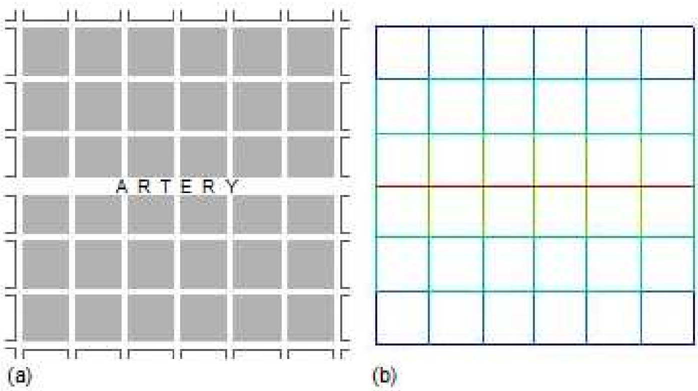


Figure 8. Type 1 unit-segment analysis. (a) Hypothetical roadway structure; land-use blocks are shown in solid shades. The central wider roadway unit is an artery, and all others are residential streets. (b) Unit-segment-integration map; integration reduces as the color of the lines changes from red to blue.

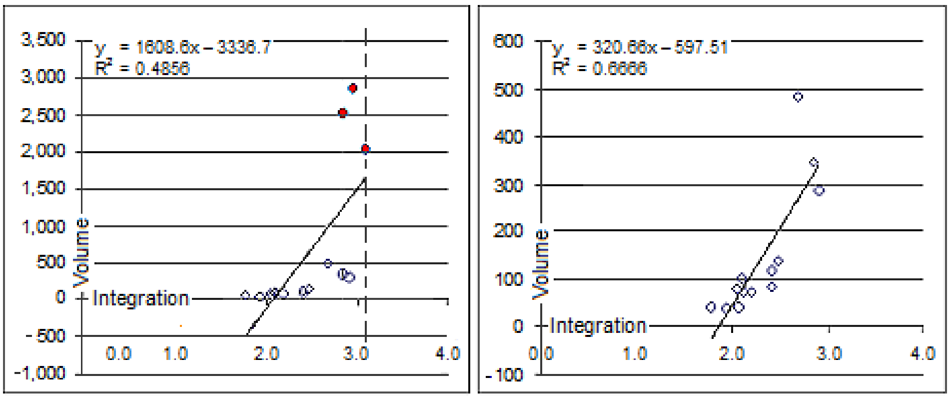
Here again, the artery is found to be the most integrated roadway unit in the entire structure [see Figure 8(b)], and the integrations of the residential streets gradually reduce as they become distantly connected from the artery in the graph (see Figure 2 for the explanation of distance in a graph). However, theoretical as the configurational measures generated by this analysis might be, the illustration reinforces the previous finding explaining the proposition that, in a unit-segment analysis, the integrated units are primarily the roadway units that have high mobility characteristics and that they are expected to receive more trips than ones that have low mobility characteristics.

The traffic correlations of type 1 unit-segment analysis, however, disclose two concerns of the space syntax approach to modeling vehicular movement networks. First, because the traffic correlation of the combined roadway units has turned out to be extraordinarily strong, it seems that there is no edge effect in the analysis results. But, as seen before, the arterial counts are found to be significantly higher than the residential counts. This irregularity of travel behavior undoubtedly draws our attention to an argument that not every trip of these arteries accesses the residential streets of the neighborhood; rather, a major portion of the arterial trips represents the vehicular flow to and from the zones adjacent to Tech Terrace. On the other hand, the integration pattern of type 1 unit-segments analysis does not reflect the configurational influence of the roadway units of these adjacent zones simply because they have not been considered while performing the integration analysis. Therefore, the strong traffic correlation of type 1 unit-segment analysis, as it appears now, does not also portray a very realistic vehicular flow pattern of the neighborhood.

Second, because no integration-movement relationships have been found in any of the two outliers, arterial or residential, (see Figure 7), their individual integration patterns evidently do not relate with their corresponding traffic-flow patterns. Surprisingly, however, these two outliers together show an extraordinarily strong integration-movement relationship accounting for the majority of the variance in their flows. Apart from the edge effect phenomenon, the local traffic rules of the residential streets might have caused this anomaly. As pointed out before, the flow characteristics of the residential streets of the neighborhood vary significantly from one another because of the local traffic rules, predominantly due to the stop or yield sign controls. The flows of the residential streets get interrupted when they face such signs and, consequently, their actual mobility characteristics reduce. It is, therefore, apparent here that the actual mobility characteristics of the residential streets are also influenced by the local traffic rules. Type 2 unit-segment analysis is an example that will explain next how the local traffic rules influence the configurational measures of the residential streets of Tech Terrace and affect their actual flows.

7.3 Type 2 unit-segment analysis

In type 2 unit-segment analysis, along with the mobility characteristics, the local traffic rules of the residential streets have also been considered while defining the unit segments. The scatterplots shown in Figure 9 illustrate their integration-movement relationships.



(a) (b)

Figure 9. Scatterplots: type 2 unit-segment analysis. (a) All-roads. (b) Residential-streets.

The scatter of Figure 9(a) shows a fairly strong post-diction accounting for nearly 50% of the variance in flows of the combined roadway units. This relationship is clearly weaker than what has been obtained in type 1 unit-segment analysis. The scatter again develops two outliers separating the arteries from the residential streets. In this case, when the outlier of the arteries is removed from the scatter, the integration-movement relationship improves quite an extent ($r = 0.82$) indicating a relatively stronger ability in capturing the true trend of flows in the residential streets than those of the previous axial and type 1 unit-segment analyses.

The integration-movement relationships of type 2 unit-segment analysis also seem to explain the edge effect phenomenon as the correlation of the combined data set has been found to be weaker than that of the residential-street category alone (see Table 2). This implies that the outlier of the arteries has caused the turmoil in the integration-movement relationship of the combined units. As the scatterplot in Figure 9(a) indicates, the integrations of these arteries [the solid dots in Figure 9(a)] have been statistically underestimated in relation to their actual flows. This suggests that the integration-movement relationship of the combined data set is expected to improve if some of the trips were to be excluded from the total flow counts of the arteries. These trips seem to be the ones that merely use the arteries without accessing the residential streets of Tech Terrace and cause edge effect while developing the configuration-movement relationship of the neighborhood.

8. Conclusions

The axial-line approach to modeling movement networks has become popular not only because it does not require cost-intensive origin-destination trip-data, but it also seeks to solve the other traffic-assignment problems that the classical models usually do not address. According to Penn et al. (1998, page 59):

> "[Classical] models are therefore seldom constructed to represent the finest scale structure of the street network and their performance at this scale is not well understood. Models are generally developed based on the travel to work trip, for which the best OD information is available; however, there is often little information available on the trip types and for other modes."

However, novel as the syntax configuration theory might be, its axial-line approach to capturing the vehicular trip-makers' route-choice decisions becomes less deterministic (Hillier et al. 1993) when applied for modeling vehicular movement networks of grid-like urban textures. Consequently, in a typical North American city, where the roadway structure is predominantly found to be grid-like, the estimation of vehicular traffic with the axial model appears to be less appropriate.

It has been argued in this study that the problem of axial analysis, particularly for the purpose of modeling vehicular movement networks, lies in the development philosophy of the axial line itself, which suggests that a trip-maker's perception of route-choice primarily rests on the awareness of travel distance (in topological terms) instead of the time-cost of travel. While new developments that emulate human travel behavior and configurational properties of networks underlying the trip-makers' route-choice decisions can be found in much newer studies (Hillier et al. 2005; Turner, 2007) published in the recent symposia proceedings of space syntax as well as in different planning journals, the key understanding of the vehicular trip-makers' route-choice decisions, the time-cost of travel, has not been appropriately dealt with in space syntax literature.

Assuming that roadway units are trip-origins and trip-destinations and that they simultaneously act as connecting route segments (Paul, 2011b) among each other, this study has shown that the mobility characteristics of these units, in terms of the time-cost of travel, influence their accessibility measures and, thus, affect their vehicular travel demands. In other words, vehicular trip-makers tend to pick roadway units that not only provide close connections to their destinations but are also less time consuming for travel.

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