Centrality Characteristics of Road Network Patterns of Traffic Analysis Zones

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Road network patterns can affect traffic performance, travel behavior, and traffic safety. Thus, a deep understanding of the properties of different network patterns can provide useful guidance for design and improvement of road systems. The aim of this study is to build a relationship between graphical and topological features of road network patterns of traffic analysis zones (TAZ) and, on the basis of this relationship, to offer a measure that can quantitatively distinguish different graphical pattern types. Toward this goal, a topological analysis measure, centrality, is applied to investigate road network patterns metrically at the TAZ level. First, 662 TAZ road networks are classified according to the graphical features of the networks; then different graphical features are calculated for centrality indices including network degree centrality, network betweenness centrality, and network closeness centrality. It is concluded that the network betweenness centrality is the best measure to distinguish and describe various TAZ road network patterns. Finally, the problem of how to assign a road that happens to be on the border of two adjacent TAZs is studied. A measure that can quantitatively describe and represent different road network patterns is offered. This measure could be useful for further evaluation of the possible effects of TAZ road network patterns on transportation.

A road network consists of different types of roads that offer specific functions. Local roads are at the bottom level of the functional classes, tending to be associated with access to buildings; collector roads pick up traffic from local roads to major arterials; and then traffic flows are channeled to upper-level roads such as intercity highways. Nodes and links of certain road types can be connected following network grammar (*1*) to form special road network patterns. When a pattern is fixed, it is consequently determined how private and public domains are linked, and thus how and where different vehicles move: whether vehicles and pedestrians can go straight from origins to destinations or whether they have to make a detour. Thus, although not the only causal factor, the network pattern can be a primary determinant of the connectivity, continuity, and efficiency of a road system (*2*) and can profoundly affect travel patterns (*3*). An appropriately designed road network pattern can create safe, quiet, and healthy environments and thus can contribute significantly to the quality of life and sustainability of an area (*4*).

To find an appropriate road network pattern, researchers should have a deep understanding not only of the graphical features that describe patterns based on researchers' understanding of road patterns but also of the topological characteristics that can offer quantified and more objective measures to describe and explain the network structure in a proper study scale—the traffic analysis zone (TAZ), which is the basic unit of transportation analysis. Traffic-related data and measurements are always aggregated and calculated at the TAZ level.

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Transportation Research Record: Journal of the Transportation Research Board, No. 2256, Transportation Research Board of the National Academies, Washington, D.C., 2011, pp. 16–24.
DOI: 10.3141/2256-03

LITERATURE REVIEW

Taking note of the effects caused by road network patterns, researchers have investigated different road network patterns by focusing on three themes: qualitative analysis and comparison of different road network patterns, quantitative analysis of virtual and simple road networks, and improvement of community road network patterns.

Qualitative Analysis of Road Network Patterns Based on Graphical Features

Different road network patterns can form different traffic flows (*4, 5*) and can affect the traffic safety (*4, 6–8*), land use efficiency (*9*), and livability (*4*) of a certain area. In these studies, road networks are classified into different kinds according to their graphical characteristics; some are classified into five categories: gridiron, fragmented parallel, warped parallel, loops and lollipops, and lollipops on a stick, which is a widely accepted classification method in road network pattern analysis (*4, 6, 10*). Another method is to distinguish road network patterns as linear, treelike, radial, cellular, and hybrid (*11, 12*). Some classifications are based on basic graphs from graph theory (*2, 13, 14*), such as grid, star, and ring (*4*); other research classifies road network patterns into organic, speculative grids, streetcar grids, and suburban hills (*15*).

Existing studies classify road network patterns into different kinds manually according to the researchers' understanding and judgment of the graphical features of the road networks. Thus the same pattern may be classified into different pattern types by different researchers. This classification can be more ambiguous and inaccurate when there are some mixed patterns that cannot be classified as any pure pattern type. Since the road network displays both geometric and topological variations, an efficient way may be to analyze both the graphical and topological features simultaneously and build a relationship between them. Thus the road network could be better understood by use of topological measures that can enable quantitative analysis and description of road network patterns. The stimulus for this study is to examine the topological characteristics of road network patterns.

Quantitative Analysis of Virtual and Simple Networks

Existing urban planning research has developed the concept of connectivity to describe how well a road network links locations between which people want to travel. Several measures of connectivity are drawn from transportation, urban planning, geography, and landscape ecology, and these measures are compared when they are applied to the same road networks of communities (*16*). Some of these connectivity measures, such as block length and link–node ratio, are used by communities across the United States (*17*). Unlike connectivity, centrality can describe how important a road is and on what level a network is centralized on certain roads. On the basis of the science of topology, centrality analysis originates in structural sociology and is introduced to study the power and importance of elements in social, biological, communication (*14, 18*), and geographic networks (*19*). Limited research on road network centrality has shown that centrality indices can nicely capture the "skeleton" of the urban structure (*20*), and these indices can allow an extended visualization and characterization of the city structure. These topological measurements are employed in research on virtual (*2, 13*) and simple networks (*14*) in order to test the performance of transportation facilities (*21*) and to simulate the evolution process of urban road systems (*2, 13*).

The limited research on urban road centrality analysis shows that centrality can describe the topological structure of a road network. It could be better than graphical classification in distinguishing different road patterns, especially mixed patterns. But these studies are not concerned with the relationship between graphical and topological features. Meanwhile, all the topological analyses focus on virtual or simple networks rather than real road networks. This study calculates topological measurements for different graphical patterns of real road networks.

Community- or Urban-Level Road Network Design and Improvement

Many studies of road network patterns tend to offer guidance for land developers and urban planners (*9*), so studies are often conducted at the community or urban level. Community-level analysis focuses on the effects of road network patterns on travel, safety, and walking environment (*4, 6*). Urban-level road structures have been studied for entire urban areas to explain which kind of road system is better for land use, urban expansion, and the environment (*2, 8, 22*). In order to compare different road networks, studies are also conducted for a particular size, such as a 1-mi^2 road network (*7, 20, 23*). In addition, some research is conducted on the basis of networks with the same amount of nodes and links to standardize the analysis procedure and results (*14*).

The TAZ is the basic unit for transportation studies, with traffic, demographic, and geometric data aggregated in it. TAZs are delineated so that they can reflect travel behavior, traffic flow performance, and traffic mode choice as a homogeneous group and so traffic-related comparisons between TAZs can be reasonable and effective. The aim of road network pattern analysis is not only to identify different types of networks but also to compare traffic conditions of different patterns in order to find an ideal network pattern to guide road design and improvement. Thus, this study is triggered by the desire to analyze road network patterns of TAZs.

STUDY OBJECTIVES

Previous studies focused on qualitative research on road network patterns, classifying road network patterns based on graphical features. Topological analysis was introduced to quantify virtual or simple road network characteristics, but relationships between graphical and topological features of real road networks are rarely studied. Much research has been done at various scales of road networks, such as the community level and the urban level. Though it would be more efficient for traffic analysis to investigate TAZ-level road network structures, such research at the TAZ level is rare yet. So the aim of this study is to examine the TAZ-level road network graphically and topologically, by focusing on exploring the structural features of various road network patterns and using topological measurements—centrality indices—in order to quantitatively distinguish and describe different road network patterns.

DATA PREPARATION

Data Selection

This study employed data from Orange County, Florida, because of two concerns: first, Orange County is a typical area in which there are diverse and many road network types. This condition guarantees the study with different road network patterns and universal meaning of results. Another important concern is the availability of data. The data for this study are directly from another research project on Orange County by the authors' research group. The authors believe that besides the obvious convenience, data sharing is a healthy interaction between the two projects, adding new dimensions and mutual correspondence to each other.

Data Sources

Two sources of data are used in this study. The Central Florida Regional Planning Model, Version 4 (CFRPM IV) provides the TAZ data, dividing Orange County into 662 TAZs. The community-extent road line data are extracted from the Master Address File/Topologically Integrated Geographic Encoding and Referencing (MAF/TIGER) database of the U.S. census, updated to July 2008.

Data Processing

In order to analyze the road network in every single TAZ, all the road line data should be divided into different TAZs. But the road line data from the census MAF/TIGER database did not contain a TAZ number field that could trace the TAZ to which every road belongs. So data processing was carried out to add the TAZ identification to each road line. This work was completed with the identity tool in ArcGIS 9.3 software. The tool generates a new road line data file in which roads can be targeted through TAZ identification.

ROAD NETWORK PATTERNS BASED ON GRAPHICAL FEATURES

According to the network graphical features, a widely accepted classification method is summarized in five categories: gridiron, fragmented parallel, warped parallel, loops and lollipops, and lollipops on a stick (*24*). Samples and descriptions are shown in Table 1, and the layouts are shown in Figure 1. These patterns are historically designed and grouped together to form the current road system in the United States. On the basis of the elements, the 662 TAZ road networks are classified into different types. In order to ensure the objectivity of the classification, a student familiar with the classification scheme was invited to do the work with the authors.

During the classification, it was found that 16% of 662 TAZ road networks are merely decentralized lines totally disconnected from each other. These networks cannot be classified into any type of pattern. The remaining 556 TAZs could be classified into different categories of patterns, 87 of which were difficult to recognize.

Of the 556 TAZs containing classifiable road networks, only 31% of the TAZ road networks contain purely one type of the five categories. More than two-thirds of them are mixtures of two types or even three. Mixed networks with two types of patterns form more than half of all these mixtures. So five categories is not enough, and several mixed patterns were added (middle pie chart, Figure 2).

Among the TAZ road networks containing pure types, the pure fragmented parallel and the loops and lollipops each accounts for more than one-third (right pie chart, Figure 2). It is obvious that loops and lollipops is more popular than other categories in Orange County, which is the same among the mixed patterns. The TAZ network patterns mixed with loops and lollipops and lollipops on a stick account for almost one-half of all the mixtures, with an overwhelming majority compared with others (left pie chart, Figure 2). If a more in-depth look is taken at the composition of these mixed patterns, it is easy to see that the occurrence rate of the loops-and-lollipops type is the highest, followed by lollipops on a stick and fragmented parallel. Of all the mixtures with two patterns types, the data show that there are 225 TAZs with road network patterns formed with mixtures of loops and lollipops. Through the analysis, it is clear that the most infrequent pattern is the warped parallel, which always forms the lowest percentage in every kind of statistical measure, whereas the most popular one is loops and lollipops.

The manual classification process is based totally on how the researcher understands and defines each kind of road network pattern, a basis which could make the classification subjective. More important, the literal and graphical description could make the classification ambiguous, especially for mixed road network patterns. In addition, frequently some TAZ road networks were subtly different from each other so that it was difficult to define the type merely according to the graphical features. For that reason, this study plans to propose a quantifiable measurement.

CALCULATION OF CENTRALITY TO DESCRIBE VARIOUS PATTERNS

Centrality Measures

Through the classification, it is easy to recognize that the primary difference between various types of road patterns is that certain roads are capable of providing a critical connection for others. In other words, does a road collect most of the other roads so that it becomes more central? Or are these roads equally important to each other? For example, roads in a gridiron pattern may seem equal to each other because most of them have the same opportunity to connect to others. In contrast, roads playing the role of sticks in the lollipops-on-a-stick pattern are more central than the lollipops because one stick road can connect with many cul-de-sacs. Centrality measurements including degree, betweenness, and closeness could quantify how central or important each node or link is inside a network, so that these measures are appropriate to describe the difference between pattern types. Thus, in this study the degree, betweenness, and closeness centrality indices are utilized to calculate the different pattern types defined in the previous section. The centrality measurements applied are all from the contribution made by Freeman (*14*). These indices are free from the effect of network size so that cross-network comparison is possible.

TABLE 1 TAZ Road Network Pattern Types

Category	TAZ Samples	Description
Gridiron	TAZ 730	Clear road pattern Four-legged intersections with right angles Straight lines Well interconnected Set of mostly parallel lines that are crossed by a second set of parallel lines
Fragmented parallel	TAZ 379	Straight lines parallel with each other partially Not well interconnected More three-leg intersections
Warped parallel	TAZ 805	Relative big curves parallel with each other More three-leg intersections
Loops and lollipops	TAZ 432	Curving streets that can form many small ring roads along with cul-de-sacs Discontinuous Insular More three-leg intersections
Lollipops on a stick	TAZ 313	Treelike roads consist of several main roads such as stems and cul-de-sacs like branches More three-leg intersections

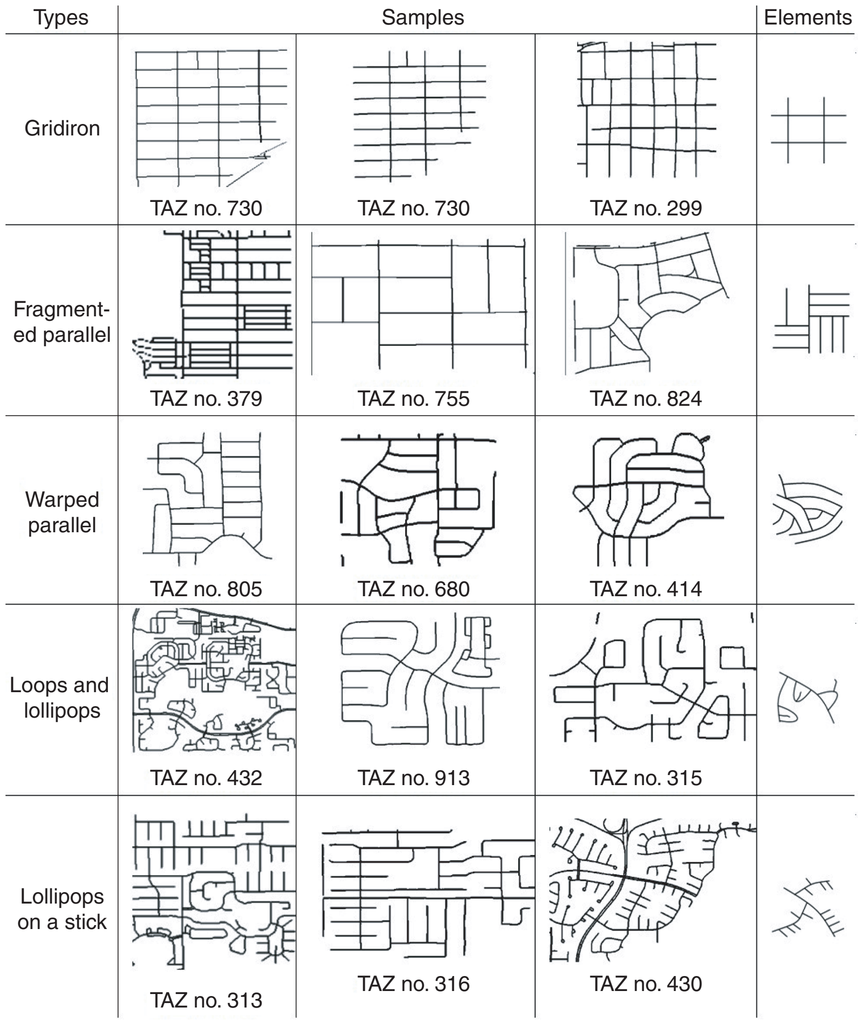


FIGURE 1 Layouts of TAZ samples used in this study.

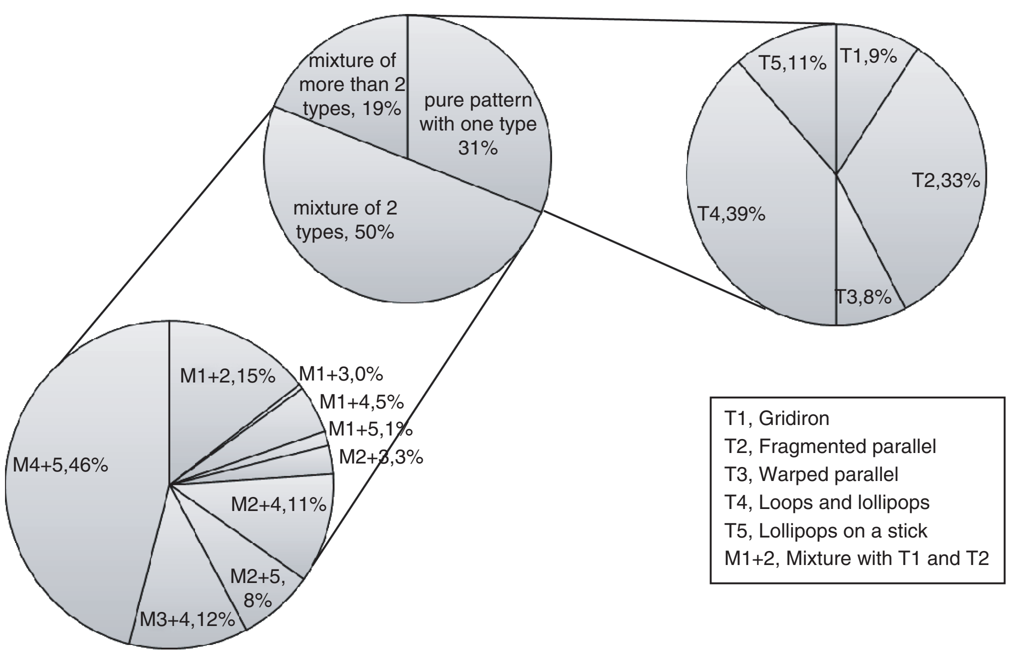


FIGURE 2 Statistical results for different types of TAZ road network patterns.

According to Freeman, "The degree of a point is simply the count of the number of other points, that are adjacent to it and with which it is, therefore, in direct contact" (*14*). The higher the degree is, the more influential a point is, because there are more other points directly connecting to it. The degree of centrality of a point is defined by

$$C_i^D = \sum_{i=1}^{n} a_{ij} \tag{1}$$

where

C_i^D = degree centrality of point i;
a_{ij} = 1 if and only if point i and point j are connected by a link, 0 otherwise; and
n = total number of points in network.

The betweenness of a point is "based on the frequency with which a point falls between pairs of other points on the shortest paths connecting them" (*14*). The higher the betweenness is, the more possible it is that a point can fall on the connection path between other points to control their communication. The degree of a point is defined by

$$C_i^B = \sum_{j}^{n} \sum_{k}^{n} \frac{g_{jk(i)}}{g_{jk}} \qquad i \neq j \neq k \tag{2}$$

where

C_i^B = betweenness centrality of point i,
$g_{jk(i)}$ = number of geodesics linking points j and k that contain point i on them,
g_{jk} = number of geodesics linking points j and k,
$\frac{g_{jk(i)}}{g_{jk}}$ = probability that point i falls on a randomly selected geodesic linking point j or k, and
$\sum_j^n \sum_k^n \frac{g_{jk(i)}}{g_{jk}}$ = overall betweenness centrality of point i, the sum of point i's partial betweenness values for all other pairs of points excluding point i.

The closeness of a point is "based upon the degree to which a point is close to all other points" (*14*). The greater the closeness is, the shorter the sum of distance is from a point to others, which means that it is easier to start from a point to any other points. The degree of a point is defined by

$$C_i^C = \left[\sum_{i=1}^{n} d_{ij}\right]^{-1} \tag{3}$$

where

C_i^C = closeness centrality of point i,
d_{ij} = number of links connecting points i and j, and
$\sum_{i=1}^n d_{ij}$ = overall level of how far point i is away from other points, so that its inverse of course shows how close it is to others.

Since this study plans to analyze the centrality property of a whole network, network centralities are applied. The network centralities are based on the point centralities, so there still will be three kinds: the network degree centrality, the network betweenness centrality, and the network closeness centrality, all defined by

$$C^X = \frac{\sum_{i=1}^{n}\left[C_{i*}^X - C_i^X\right]}{\max \sum_{i=1}^{n}\left[C_{i*}^X - C_i^X\right]} \tag{4}$$

where

C^X = network centrality from perspective of degree of betweenness or closeness,
C_i^X = one of point centralities defined above,
C_{i*}^X = largest value of C_i^X any point could get in network, and
$\sum_{i=1}^n [C_{i*}^X - C_i^X]$ = observed sum of differences to every point's maximum value.

Consequently, max $\sum_{i=1}^n [C_{i*}^X - C_i^X]$ defines the possible maximum sum of these differences. Thus, C^X is defined as "the average difference between the relative centrality of the most central point and that of all other points" (*14*).

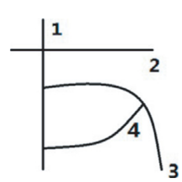
Transformation of Road Network into Topological Network

Before network centralities are calculated, it is necessary to simplify the real road network into a topological network consisting of nodes and links. There are two ways to do this: the primal approach and the dual approach (*20, 23*). The primal approach is based on a quite simple, intuitive representation of networks that turns intersections into nodes and roads into edges; the dual approach is the opposite, turning roads into nodes and intersections into edges. If the primal network is analyzed with centrality indices, the focus will be on the intersections. Otherwise, if the dual network is calculated, the measurements will describe the road characteristics. As discussed earlier in this section, this study emphasizes the differences of importance, centrality, and power between roads to describe various kinds of network patterns, so the dual approach is proper. The procedure of simplifying road networks is as follows:

Step 1. Number every road in the network. If two roads form the largest convex angle at intersections, merge them as one road (Figure 3*a*).
Step 2. Write out the adjacent matrix of the network. Write the numbers of roads in both the title row and the title column; the elements in the matrix record whether a pair of roads is directly connected. The element will be 1 if the two roads are directly connected, otherwise 0 (Figure 3*b*).
Step 3. Visualize the adjacent matrix with a net graph. Draw as many points as the number of roads; if a pair of roads shares the same intersection, draw a link between the points assigned the numbers of the two roads (Figure 3*c*).

Measurement Calculation

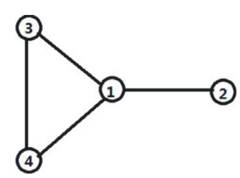
All three network centrality indices were calculated for the TAZ road network. From the classification results, five types of TAZ road



(a)

	1	2	3	4
1	0	1	1	1
2	1	0	0	0
3	1	0	0	1
4	1	0	1	0

(b)



(c)

FIGURE 3 Procedure for transforming real road networks by dual approach: (*a*) Step 1, (*b*) Step 2, and (*c*) Step 3.

networks were chosen to be illustrated in Table 2 along with their network centrality indices, and layouts of the networks are shown in Figure 1. The calculation results in Table 2 and Figure 4 reveal the following observations:

1. All three measures of network centrality agree with minimum values in describing the gridiron pattern type;
2. All three measures of network centrality agree with higher values in ranking from the gridiron to the lollipops-on-a-stick pattern type;
3. Measures of network betweenness centrality rank from smallest to biggest as the pattern types range from gridiron to lollipops on a stick;
4. The network betweenness centrality presents the greatest range of variation in values when different kinds of pattern types are described; thus network betweenness centrality is "finer grained" than others (*14*);
5. The network degree centrality presents the smallest range of variation in values, so it is the "coarser grained" measure (*14*); and
6. It can be concluded that traffic flows will more possibly be distributed unequally along with the increase of betweenness centrality from the gridiron pattern to the lollipops-on-a-stick pattern.

Thus, the road network is more central to certain roads in patterns with more lollipops and loops than in patterns with grid structures.

The network betweenness centrality index can well distinguish different types of TAZ road network patterns. The most important advantage of this index is that it can avoid the size difference between TAZs because of its relativity. A higher value of network betweenness centrality presents a network in which more roads become the only connection to other roads. This finding means that some roads are more central and important than others. According to the calculation results, the gridiron pattern has the lowest value of network betweenness centrality, which means that every road has the same chance to connect to others and thus they are equally important; the fragmented parallel and warped parallel patterns have more chance to have central roads; the lollipops-on-a-stick pattern has the highest value of this index, showing that some roads are overwhelmingly central, connecting almost all of the other roads like the stem of a plant.

BOUNDARY ROAD ASSIGNMENT

The discussion in this section concerns how to treat roads that happen to be on the border of two adjacent TAZs. The delineation of the TAZ is based on many factors, such as road system, landscape, water, and communities. Many TAZs are separated along major roads, so it is common for the boundaries of TAZs to overlap with the major roads, as in the upper diagrams in Figure 5. The question is, if a road happens to be on the border of two TAZs, how is this boundary road assigned? Should the boundary be assigned to both TAZs, or to one of them, or to neither of them? Various ways of assignment are illustrated in the bottom of Figure 5. Before these questions are answered, the effect of the boundary on different networks should be analyzed.

In this study five types of TAZ road networks were randomly selected to test the boundary effect. To every TAZ network, a boundary is added on one side, two sides, three sides, and four sides of the network in order to check the change of betweenness centrality values. The results are shown in Table 3, and the layouts of the networks are shown in Figure 1. When boundaries are added to the original networks, network betweenness centralities are all changed among the network patterns. However, the rank of the values of network betweenness centrality of the five types stays the same: the smallest with the gridiron pattern to the biggest with the lollipop-on-a-stick pattern. Obviously, the range of variation of index values becomes smaller when the boundary is added, as shown in Figure 6. The network betweenness centrality does not work well when there is a boundary around the network. So when the TAZ road networks are compared or analyzed with the network betweenness centrality, it is recommended that roads on the border of two TAZs not be assigned to either TAZ.

DISCUSSION OF RESULTS

As described in previous sections, this study focuses on TAZ-level road network structures. Some typical road network patterns are randomly selected to be calculated and analyzed, and there still remain several issues that need further study.

The aim here is to show the possibility of using centrality measures to distinguish road network patterns, not to summarize the regularity. So the road network samples calculated are limited, not including all 662 TAZ road networks. More characteristics and regulations could be determined with more data.

This study is based on the existing TAZ delineation, which is used in the traffic forecasting model of Central Florida. It is true that how to choose the analysis unit will significantly influence the calculation and analysis results. Different treatment of the boundaries of TAZs could form the modifiable areal unit problem (*25*). These problems are important when it comes to spatial analysis, but this study planned to put the focus on how to describe the graphical and topological features for a certain road network in a TAZ. The way to create and modify a TAZ or a certain analysis unit is not the task of this study, but it should be studied in future research.

Two special networks need further study: networks containing various types of patterns and networks consisting of several unconnected parts of roads. During the analysis, it was found that the mixed pattern tends to have higher values of betweenness centrality indices than the pure pattern does. Preliminary results show that unconnected road networks often present betweenness centrality that is abnormally lower than expected.

The purpose of this study is not limited to the centrality calculation. Many other topology measures can describe the structural characteristics of a network. A future goal is to use the centrality index or other better measures to represent different kinds of road patterns and then to analyze the relationship between road patterns and travel behavior, traffic incidents, and congestion. With these future studies, planners and engineers could clearly understand which kind of road network pattern is better to encourage walking and bicycling, reduce crashes, and improve transit services so as to form a sustainable, livable community.

CONCLUSIONS

Road network structure affects traffic performance, transportation safety, and even social activities in an area. To evaluate the effects of road network patterns on traffic circulation, first it is important to describe and understand different road network patterns at the TAZ level. Besides, traffic-related data are conventionally aggregated in

TABLE 2 Centrality Index Calculation Results of Different Types of TAZ Road Network Patterns

Centrality Index	Network				
	Gridiron Pattern TAZ 730	Gridiron Pattern TAZ 299	Fragmented Parallel TAZ 755	Fragmented Parallel TAZ 824	Warped Parallel TAZ 680
Network degree centralities (%)	2.64	19.23	25	25.74	26.37
Network betweenness centralities (%)	14.24	13.52	28.34	27.92	44.23
Network closeness centralities (%)	16.01	21.67	37.89	30.41	44.15

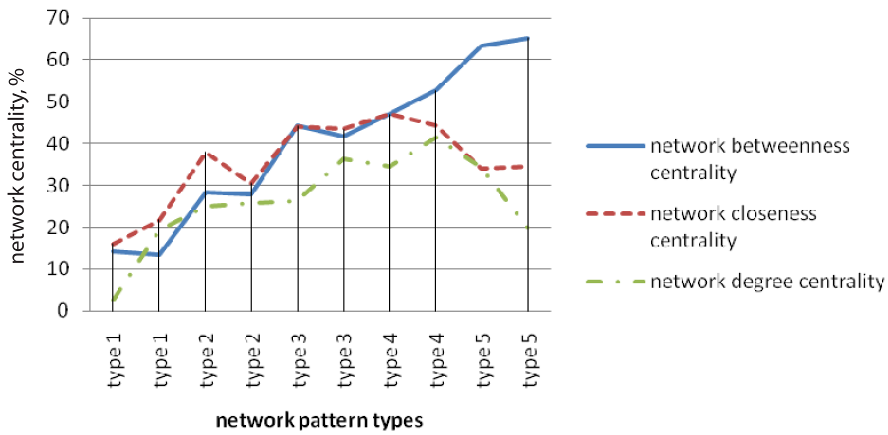


FIGURE 4 Centrality indices of different types of TAZ road network patterns.

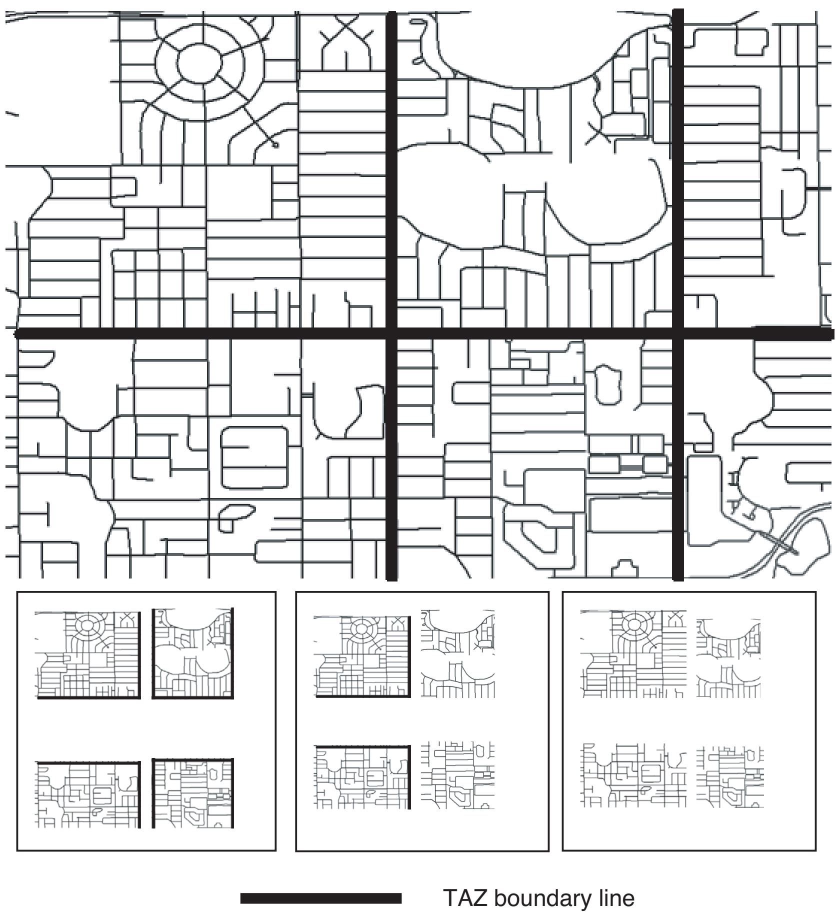


FIGURE 5 Boundary problem during TAZ road network analysis.

Warped Parallel TAZ 414	Loops and Lollipops TAZ 913	Loops and Lollipops TAZ 315	Lollipops on a Stick TAZ 316	Lollipops on a Stick TAZ 430
36.36	34.55	41.43	34.29	19.83
41.65	47.02	52.74	63.36	65.26
43.48	47.12	44.38	34.06	34.52

TABLE 3 Boundary Effects on Values of Network Betweenness Centrality

	Network Betweenness Centrality (%) by TAZ				
Boundary Type	TAZ 299	TAZ 755	TAZ 805	TAZ 913	TAZ 316
Original	13.52	25	36.30	47.02	63.36
Boundary on 1 side	11.01	26.69	34.23	40.61	54.84
Boundary on 2 sides	11.52	27.92	34.59	40.61	50.45
Boundary on 3 sides	11.52	27.92	30.31	40.61	50.45
Boundary on 4 sides	17.61	22.33	28.16	47.90	48.39

the TAZ, so the TAZ becomes the basic study unit and motivates the idea of studying the road network structure at that level.

In this study the graphical classification of road network patterns is summarized and 662 TAZ networks of Orange County, Florida, are classified. It is found that not all TAZ road networks can be easily recognized as a certain type: some networks consist of unconnected roads and some are very difficult to classify. More than one-third of the classifiable TAZ road networks are pure pattern types; the remaining ones are mixtures of two or more types. Among all TAZ road networks, the loops-and-lollipops pattern is the most widely used pattern in network design.

Topological analysis using centrality is applied to describe the topological characteristics of different network patterns. First, a dual approach to the transformation of a real road network into a topological network is presented. On the basis of the simplified networks, the centrality measurements, including network degree centrality, network betweenness centrality, and network closeness centrality, are explained and indices are calculated for typical road network patterns. It is obvious that the network betweenness centrality is a finer-grained measure, which can distinguish different pattern types.

In order to appropriately assign a road on the border of two adjacent TAZs, the boundary effect was analyzed. Along with adding the boundary to original road networks, it was found that the betweenness centrality measurement becomes coarser grained. So it is recommended that boundary roads be removed before centrality calculation.

The centrality indices offered here can distinguish and quantitatively describe the road network patterns. This measure may be used to build relationship models evaluating effects of TAZ road network patterns on traffic performance, safety, and environment.

ACKNOWLEDGMENT

This study is supported by the Shanghai Pujiang Program Safety Evaluation of Urban Transportation Planning and Management Based on Statistical Methods.

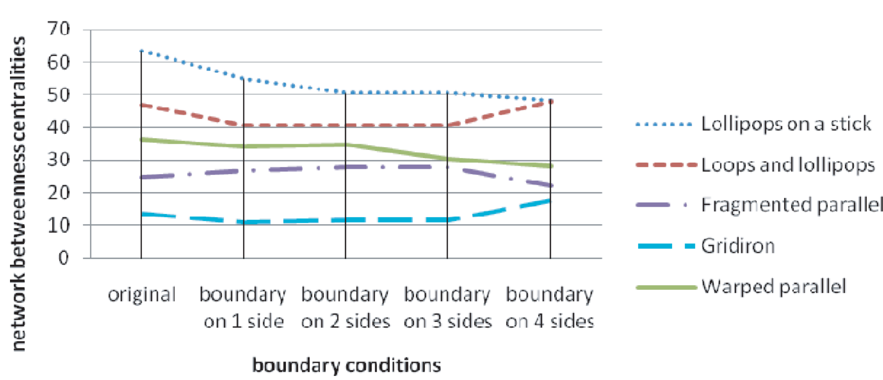


FIGURE 6 Results of calculations of network betweenness centrality for different boundary conditions.

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The Urban Transportation Data and Information Systems Committee peer-reviewed this paper.