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Research Article

Evaluating the Connectivity and Imbalance Contribution of New Sections towards Highway Network: A Complex Network Perspective

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The evaluation of the impacts of new sections on the highway network is an essential aspect of the feasibility study. Existing studies predominantly concentrated on engineering-oriented feasibility assessments, often overlooking their potential effects on parallel sections and the overall network. In this research, we present an evaluation model for new sections based on complex networks, focusing on the connectivity and imbalance of transportation networks. This model serves as a supplementary approach for enhancing the feasibility analysis of new highway projects. The model comprises three distinct modules, namely, complex network, eigenvalue, and evaluation. Therein, the complex network provides diverse attributes for sections with the dynamic edge weights. Moreover, probability betweenness centrality and volume betweenness centrality have been presented as an eigenvalue of sections based on the multilayer complex network. Furthermore, the connectivity evaluation based on the eigenvalue and the imbalance evaluation based on the entropy and Gini coefficient are conducted. Through the case study, the results of the model demonstrate the connectivity and imbalance contribution of new sections and provide a novel perspective for the feasibility study.

1. Introduction

The planning, construction, and operation of highways have resulted in the emergence of regionalization and networking in the transportation systems engineering [1], as there has been an improvement in the connectivity of infrastructure. However, the increasingly complex highway network has exhibited a spatial-temporal imbalance that may have an adverse impact on traffic, leading to the waste of the highway's resources. The new sections can redistribute traffic assignment in the network impacting the associated sections and the overall network. However, quantitative measure of the impacts on the partial and overall network imbalance is lacking, and the dynamic features of traffic on the road sections and network are not precisely assessed in the feasibility study of new road sections [2]. Therefore, the evaluation of the impact of new sections on the network and the associated sections is necessary. In our study, we present an evaluation model that evaluates the impact of new sections on the connectivity and imbalance using the complex network methodology. The connectivity refers to the ability of the road section to facilitate transportation that reflects the significance of sections in the network, and the imbalance represents the distribution of property in the network that reflects the network stability. The connectivity and imbalance contribution of new sections can be evaluated with the model.

The remainder of this paper is organized as follows. "Related Work" (Section 2) offers the comprehensive overview of the current literature related to the research. In "Methodology" (Section 3), we introduce the evaluation model for new sections in details. "Case Study" (Section 4) then performs the detailed analysis of new section's impacts for the case study. Finally, conclusions and future directions are presented in "Conclusions and Future Directions" (Section 5).

2. Related Work

In the existing researches, the complex network methodology has been adopted to study the highway network which transforms highway elements and their relationships into nodes and edges in networks, which can be used to describe the behavior of the system and the relationships of elements in the network [3–5]. Villas Boas et al. [6] established a complex network of highways with cities as nodes. Xiao [7] analyzed the complexity of the highway network structure by establishing a road network structure based on logical relationships of elements. Xu et al. [8] established a directed network from the data of the signal control system of a city traffic system and evaluated the performance of key nodes. Costa et al. [9] used indicators such as the node degree, average shortest distance, and betweenness centrality for performance measurement. On one hand, the impacts of new sections can be assessed and some methods have been proposed for evaluating the connectivity, such as roadway capacity and the level of service as outlined in the highway manual [10], travel time analysis by Schrank and Lomax [11], and user satisfaction-based evaluation by Levinson and Lomax [12]. Moreover, Schrank and Lomax [13] and Brown et al. [14] used congestion indicator based on the traffic volume, travel distance, and travel time to assess the degree of congestion. Shim and Yeo [15] used indicators such as in degree, out degree, and betweenness centrality to evaluate the connectivity. Feng [16] proposed the connectivity based on the network stability evaluation. Tian et al. [17] and Ando et al. [18] used the section length, capacity, and efficiency to evaluate the road network connectivity. Liu and Yan [19] used current-flow efficiency to evaluate the network connectivity performance. On the other hand, the imbalance is another part of the evaluation. Zheng et al. [20] used the node degree, point intensity, intensity distribution and average shortest path in the network, and clustering coefficient, etc., for balance analysis. Li et al. [21], Sun et al. [22], and Yu et al. [23] analyzed the imbalance feature of spatial-temporal distribution of expressways at the micro-aspect by considering factors such as travel time and occupancy rate. Deng [24] analyzed the imbalanced spatial-temporal distribution of traffic volume of a single section or route of the highway. For the imbalance analysis, indicators such as road network area density and road transportation density have been selected by He et al. [25] and Fang [26]. Dai [27] studied the imbalance of traffic. Furthermore, in the feasibility study of newly constructed road sections [2, 28], the four-stage prediction method was utilized to analyze and predict the traffic volume, in terms of annual average daily traffic volume, to determine the capacity of new road sections. However, the analysis of traffic off-peaks and peaks has been lacking in detail.

Drawing on these research studies, it can be concluded that the evaluation of road networks is typically predicated on the one aspect, i.e., network's structure or traffic. Each approach reveals unique features of the network from diverse perspectives. Nevertheless, the common challenge arises in accurately accounting for the impacts of new sections on parallel sections and network structure. In details, the connectivity of parallel sections and the imbalance of network are affected by the new sections and accurately assessing these impacts remains problematic.

3. Methodology

3.1. Problem Formulation. The highway system, characterized by the bidirectional traffic flow and fully enclosed operation, is represented with the directed weighted network based on neighboring nodes, and this paper evaluates the impacts of new sections from the following two aspects.

Definition 1. Connectivity is the ratio of property between the section and network that reflects the importance of the section in the network. The formula is expressed as follows:

$$C_e = \frac{f(e)}{f(G)}, \tag{1}$$

where C_e represents the connectivity of section, e is the road section in the network, G is the network, and $f(e)$ and $f(G)$ are the functions of property on the section e and network G, respectively.

Definition 2. Imbalance is the sum of the equilibrium function of elements that reflects the degree of unequal distribution in the network. The formula is expressed as follows:

$$I = \sum(f(\gamma)), \tag{2}$$

where I represents the imbalance, γ is the property of sections, and $f(\gamma)$ represents the equilibrium function.

The impact of new sections on parallel sections can be analyzed by assessing their connectivity, which reflects the change of importance of both new and parallel sections. In addition, network imbalance can provide insight into the trend of the distribution of network property.

3.2. The Evaluation Model for New Sections. The evaluation model for new sections encompasses three interrelated modules, namely, complex network, eigenvalue, and evaluation. The module "complex network" encompasses the multilayer network, which is further composed of the structural network, weighted network, and origin-destination (OD) network. In the module "eigenvalue," two betweenness centralities are conducted based on the module "complex network" to capture both structural and traffic features of road sections. Finally, in the module "evaluation," the imbalance analysis and connectivity analysis are implemented. Figure 1 visually illustrates the composition of the model and intricate relationship between these modules.

3.2.1. Complex Network of the Highway. The structural network denotes as directed by the graph $G = (V, E, A)$, which represents the connection relationships of elements in the highway system. These elements include nodes and edges. Nodes correspond to entrances and exits of highway,

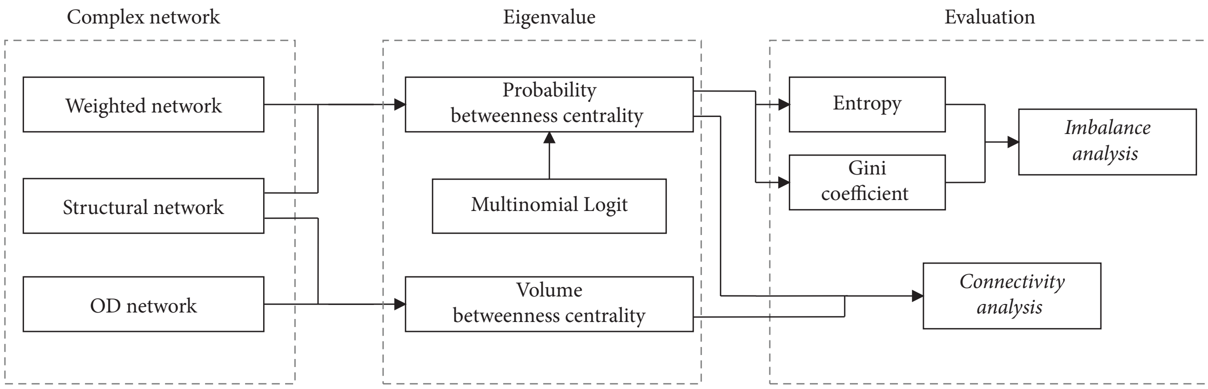


Figure 1: The evaluation model for new sections based on the complex network.

which are described as a set containing m nodes, denoted as $V = \{v_1, v_2, \ldots v_m\}$. The directed edges are represented as $E = \{e_1, e_2, \ldots e_n\}$, which is the set of the road section between nodes. The adjacency matrix for nodes, denoted as $A \in \mathbb{R}^{n\times n}$, signifies the existence of the connection as follows: if the road section $e_{\text{ij}} = (v_i, v_j)$ exists, then $a_{\text{ij}} = 1$; otherwise, $a_{\text{ij}} = 0$.

In addition, in the weighted network, the weight is the generalized cost function of the edge, defined as w_{ij} that consists of the road toll, vehicle operating cost, and time value cost. Due to traffic varying over time, the dynamic edge weights based on the traffic volume are constructed to capture the dynamic properties accurately. The mathematical expression of the generalized cost function is presented in the following equation:

$$w_{\text{ij}} = K_{\eta\text{ij}} + \delta_\eta \times L_{\text{ij}} + \varphi_\eta \times T_{\text{ij}} \times \left[1 + \alpha\left(\frac{v_{\text{ij}}}{C_{\text{ij}}}\right)^\beta\right], \quad (3)$$

where w_{ij} represents the general cost of the section e_{ij}; $K_{\eta\text{ij}}$ is the road toll of the vehicle type η passing the section e_{ij}; δ_η is the operation cost of the vehicle type η (including fuel, tyre wear, and car maintenance) [29]; L_{ij} is the length of the section e_{ij}; φ_η is the time cost of the user; T_{ij} is the travel time of vehicles in free-flow condition; v_{ij} is the traffic volume; C_{ij} is the road capacity; and α and β are hyperparameters of the travel time.

Furthermore, moving on to the OD network, each trip contains this information, such as vehicle's plate number, vehicle type, origin, destination, departure time, and arrival time. The collection of all trips forms the OD network. Finally, with the multilayer network, the evaluation model can analyze the highway systems accurately.

3.2.2. Eigenvalue of the Road Section. The eigenvalue of the road section consists of probability betweenness centrality and volume betweenness centrality that are involved with the road structure and traffic, respectively, and reflect the significance of each road section in transportation supply and demand [30].

(i) Probability betweenness centrality of road section based on the multinomial logit.

In transportation networks, probability betweenness centrality is the probability that the road section is contained in the paths of OD pairs in the network. This measure serves as an indicator of the road section's connectivity in the transportation supply. The higher the probability betweenness centrality is, the greater the connectivity of the road section towards the network will be. The mathematic formula is expressed as in the following equation:

$$pb_{e_{\text{ij}}} = \frac{1}{N(N-1)} \sum_{s=1}^{N}\sum_{t=1}^{N}\sum_{m\in M_{\text{st}}} p_{\text{st},m}\xi_{\text{st},m}^{e_{\text{ij}}}, \quad (4)$$

where $\text{pb}_{e_{\text{ij}}}$ is the probability betweenness centrality for the section e_{ij}; $p_{\text{st},m}$ represents the probability that the m[th] path of the OD (s,t) pair is chosen; $\xi_{st,m}^{e_{\text{ij}}}$ is a variant of 0 or 1; if the m[th] path consists of the section e_{ij}, then $\xi_{\text{st},m}^{e_{\text{ij}}} = 1$; otherwise, $\xi_{\text{st},m}^{e_{\text{ij}}} = 0$; N is the number of nodes; and M is the number of available paths of the OD (s,t) pair.

To obtain the path choice probability, the study adopts the multinomial logit (MNL) model that is a general tool most widely used to model the travel behavior of transportation system users. This approach calculates the probability based on their weights; the formula is expressed as in the following equation:

$$p_{\text{st},m} = \frac{e^{[-\theta(w_m+\phi)]}}{\sum_{l=1}^{M} e^{[-\theta(w_l+\phi)]}}, \quad (5)$$

where $p_{\text{st},m}$ is the probability that the m[th] path is chosen; θ and ϕ are discrete parameters; w denotes the weight of each path as systematic utility; and M is the number of available paths of each OD (s,t) pair.

(ii) Volume betweenness centrality of the road section.

Volume betweenness centrality is the ratio of the traffic volume on the section to the total traffic volume in the network over a statistical period. This measure serves as an indicator of the road section's connectivity in transportation demand. Volume betweenness centrality is affected by the spatial-temporal traffic; the higher the value is, the greater the connectivity of the section is.

$$vb_{e_{ij}}(\mathrm{T}) = \frac{\sum_{s,t\in V}\sum_{\eta}\sum_{m=1}^{M}\tau_{\eta} q_{\mathrm{st}}^{\eta} p_{\mathrm{st},m}^{\eta} \mu_{\mathrm{st},m}^{e_{ij}}}{\sum_{s,t\in V}\sum_{\eta}\tau_{\eta} q_{\mathrm{st}}^{\eta}}, \quad (6)$$

where $\mathrm{vb}_{e_{ij}}$ is volume betweenness centrality of the section e_{ij}; T is the statistical period; τ is the conversion coefficient; η is the vehicle type; q_{st}^{η} is the volume of η type vehicle for the OD (s,t) pair; $p_{\mathrm{st},m}^{\eta}$ represents the ratio that the m$^{\mathrm{th}}$ path of the OD (s,t) pair is chosen for $\mu_{\mathrm{st},m}^{e_{ij}}$ is 0 or 1; if the m$^{\mathrm{th}}$ path contains the section e_{ij}, then $\mu_{\mathrm{st},m}^{e_{ij}} = 1$; otherwise, $\mu_{\mathrm{st},m}^{e_{ij}} = 0$; and M is the number of available paths of the OD (s,t) pair.

3.2.3. Evaluation on the Connectivity and Imbalance of New Sections. The connectivity and imbalance contributions of new sections towards highway network can be analyzed with these eigenvalues. The following will explain the evaluation in details:

(1) Connectivity Analysis. Connectivity attribution contains traffic supply and demand aspects, specifically denoted as probability betweenness centrality and volume betweenness centrality in this study. By calculating the connectivity of road sections prior to and following changes in the road network structure, the impact of new road sections on the parallel sections can be evaluated.

(2) Imbalance Analysis Based on Entropy and Gini Coefficient. To evaluate the imbalance, the concept of the entropy and Gini coefficient are adopted as indicators. By analyzing the temporal and spatial imbalance on the probability betweenness centrality, the influence of new sections on the imbalance is evaluated for the feasibility study.

Entropy is a measure of the degree of intrinsic properties change within a system. The mathematical formula can be expressed as in the following equation:

$$S = -\sum_{i} \frac{a_i}{\sum a_i} \ln\left(\frac{a_i}{\sum a_i}\right), \quad (7)$$

where S represents the entropy value, and a_i represents the property value.

The Gini coefficient, a widely used measure of the inequality of a distribution, is utilized to evaluate the imbalance of system properties. Specifically, it enables the assessment of the imbalance in the allocation of resources. The Gini coefficient increases as the degree of imbalance rises. The following equation provides the mathematical expression:

$$\begin{aligned} \mathrm{Gini} &= 1 - \frac{1}{N}\sum_{i=1}^{N}\left(2\sum_{k=1}^{i} w_k - w_i\right), \\ w_n &= \frac{d_n}{\sum_{j=1}^{N} d_j}, \end{aligned} \quad (8)$$

where Gini represents the Gini coefficient; d_n is the value of the property; and N denotes the number of road sections.

These concepts can be clarified by some examples. Table 1 demonstrates four examples with different conditions for the imbalance analysis. In example 1, the before and after distributions are even distribution; the entropy increases while the Gini keeps the same. In example 2, the condition is increasing an invalid section, i.e., "3": 0.0; the entropy keeps the same while the Gini increases. In example 3, the condition is changing the distribution order; both the entropy and the Gini keep the same. In example 4, the condition is closer to even distribution; the entropy increases and the Gini decreases. From these examples, we can conclude that the entropy increases or the Gini decreases means more balance and both the entropy and the Gini coefficient are adopted together for accurately evaluating the imbalance.

4. Case Study

4.1. Data Information. The evaluation model is validated with the highway network of the Guangdong-Hong Kong-Macao Greater Bay Area (the Greater Bay Area, GBA) in China (see Figure 2). The dataset of the study area comprises road network structure data and vehicle trip data that were collected over a period of seven days from July 5, 2021, to July 11, 2021. The data format is illustrated in details in Tables 2–4 that contains node information, road section information and their connection relationship, and trip information.

The Pearl River Estuary cross-river highway consists of six sections, namely, A, B, C, D, E, and F, as shown in Figure 3. At present, sections A, B, and D bear the cross-river traffic that the average daily traffic volume is 337 k passenger car unit (PCU) and increases over time, so these roads are facing great traffic pressure. Fortunately, sections C and E are currently under construction and section E is an eight-lane bidirectional highway designed for the speed limit of 100 km/h, scheduled to be opened to traffic in 2024. Section C is a sixteen-lane bidirectional highway designed for the speed limit of 100 km/h and is expected to be opened to traffic in 2027. The evaluation model was adopted for assessing the impacts of the new sections C and E on the network and the parallel cross-river roads, i.e., sections A, B, D, and F.

4.2. Complex Network Based on the Directed Edge Weight

4.2.1. Establishment of Complex Network. For the highway network in the Greater Bay Area, the network has been established with 764 nodes and 1730 edges, and the edges of the network are assigned dynamic weights. The network is depicted in Figure 3.

Table 1: Examples for the imbalance analysis.

	Changes of conditions	Attribute {"section": Property} existing ⟶ future	Entropy		Gini	
			existing ⟶	future	existing ⟶	future
1	Even distribution, increase section	{"0": 1/3, "1": 1/3, "2": 1/3} ⟶ {"0": 1/4, "1": 1/4, "2": 1/4, "3": 1/4}	1.0986	1.3863	0	0
2	Increase invalid section	{"0": 0.6, "1": 0.2, "2": 0.2} ⟶ {"0": 0.6, "1": 0.2, "2": 0.2, "3": 0.0}	0.9503	0.9503	0.2667	0.45
3	Change the distribution order	{"0": 0.5, "1": 0.3, "2": 0.2} ⟶ {"0": 0.2, "1": 0.3, "2": 0.5}	1.0297	1.0297	0.2	0.2
4	More closer to even distribution	{"0": 0.6, "1": 0.2, "2": 0.2} ⟶ {"0": 0.5, "1": 0.3, "2": 0.2}	0.9503	1.0297	0.2667	0.2

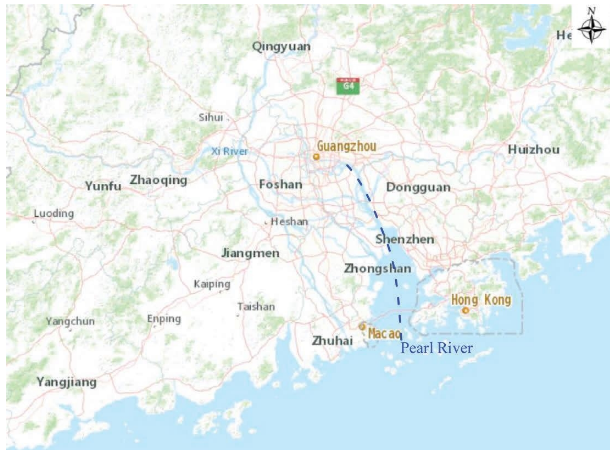


Figure 2: The Greater Bay Area in maps.

Table 2: Node information.

	Node name	Station hex	Latitude	Longitude
1	LT	040001	23.07	113.36
2	DXC	040002	23.05	113.37
—	—	—	—	—

Table 3: Road information and connection relationship.

	Node i	Node j	Gantry hex	Length	Lanenum	Speed limit
1	LT	DXC	4C2801	4440	4	100
2	DXC	LT	4D2802	4440	4	100
—	—	—		—	—	—

4.2.2. Dynamic Characteristics of Edges. The two parameters α and β were taken as $\alpha = 0.25$ and $\beta = 2.20$ in equation (3) (values were taken from the results of parametric regression calibration of travel time using the highway traffic date). The dynamic weight of the edge was established based on the traffic volume. The dynamic characteristics can be clarified by the example in Figure 4; therein, the trend of dynamic weights for section A is in alignment with the corresponding traffic volume.

4.3. Connectivity Analysis. There are three parameters that need to be determined, i.e., θ, ϕ, and M in equation (5). The larger the value of θ, the more familiar the road users are with the road network. Its value depends on $\theta^2 = \pi^2/6\delta^2$, where δ^2 is the variance of random residuals in the random utility theory. By calculating with samples, $\theta = -4.0$; ϕ is the compensation parameter, here $\phi = 0$. Considering the road network's scale, the deviation of the probability betweenness centrality, and the calculation cost, M is taken as 3, i.e., $M = 3$.

4.3.1. Static Connectivity Analysis. According to whether the network includes the new section C or E, the network could be named as the existing network (without new sections) and the future network (with new sections). Figure 5(a) illustrates the distribution of the probability betweenness centrality in the existing network; as the value varies, the chromaticity shifts accordingly, and higher values yield a shift towards the red end of the spectrum and lower values result in a shift towards the blue end. To calculate the volume betweenness centrality, the average volume value during the period of 7:00–19:00 from July 5 to 11, 2021, was utilized. Gray sections in Figure 5(b) denote missing data or not yet opened.

In Figure 5, we can conclude that a minority of sections plays a pivotal role in the connectivity, and the distribution of probability betweenness centrality and volume betweenness centrality is relatively consistent that shows approximate equilibrium between transportation supply and demand. However, it should be noted that there is no positive correlation between probability betweenness centrality and volume betweenness centrality for some sections, as illustrated in the red ellipse in Figure 6; each point represents a distinct road section, and these sections exhibit lower probability betweenness centrality but higher volume betweenness centrality. As such, the assessment of the connectivity should be the combination of both probability betweenness centrality and volume betweenness centrality.

For the cross-river sections, Table 5 shows the changes of the connectivity in the existing and future networks, where pb_{i_b} and pb_{i_a} denote probability betweenness centrality of

Table 4: Trip data.

	Pass ID	Gantry hex	Through time	Vehicle type	Endstation hex	End time
1	000000430119288498588320210705002007	4C2003	2021-07-05 00:22:18	1	032009	2021-07-05 00:20:07
2	00000000960012B492178D20210705003516	4D0125	2021-07-05 00:40:12	2	032009	2021-07-05 00:35:16
—	—	—	—	—	—	—

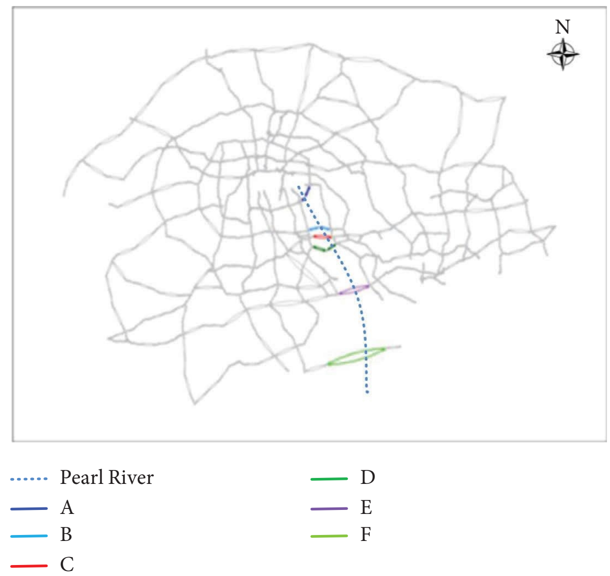


Figure 3: The network for the Greater Bay Area.

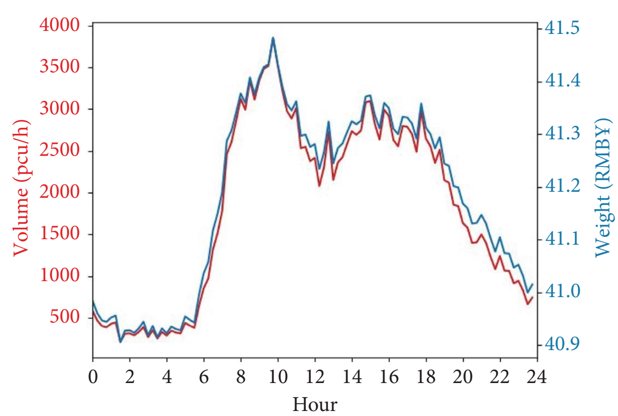


Figure 4: Traffic volume and edge weight of section A.

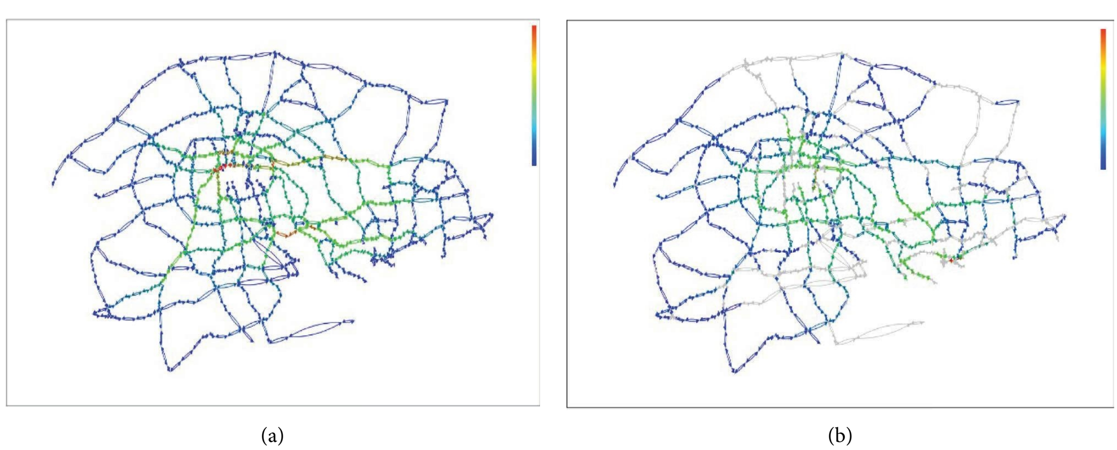


Figure 5: Section's property in the network. (a) Probability betweenness centrality. (b) Volume betweenness centrality.

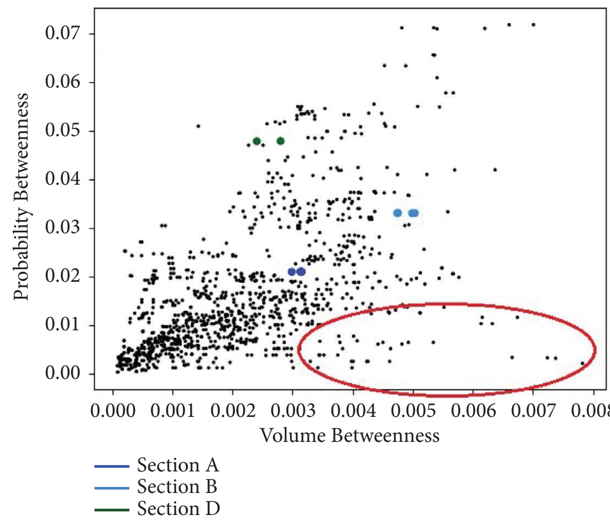


Figure 6: Probability betweenness centrality and volume betweenness centrality.

the cross-river sections in the existing and future network, respectively, and vb_{i_b} and vb_{i_a} are volume betweenness centrality in the existing and future network, respectively. As the new sections have not yet been opened, the values of vb_{i_a} for the future network are unavailable.

From Table 5, it can be concluded that $\sum pb_{i\_b} = 0.1046$ for section ABDF and $\sum pb_{i\_a} = 0.1095$ for section ABCDEF; both values are approximately equal to each other and that means the new sections do not significantly increase the overall probability betweenness centrality of the cross-river roads and only redistribute the traffic on these sections. Furthermore, the analysis shows that section D in the existing network has the highest probability betweenness centrality, while section C in the future network has the highest probability betweenness centrality; the new sections have a significant impact on the connectivity of sections B and D, while sections A and F are minimally affected. To summarize, the new sections have an impact on the connectivity of the cross-river roads when sharing the traffic pressure of sections B and D but have little impact on the overall network. Notably, due to the traffic prohibition of large buses and all trucks, section D has higher probability betweenness centrality but lower volume betweenness centrality compared to sections A and B.

4.3.2. Dynamic Connectivity Analysis. The edge weight and path selection are affected by the spatial-temporal traffic volume; meanwhile, the probability betweenness centrality and volume betweenness centrality change with the traffic. To investigate this relationship, the temporal features of connectivity in sections A, B, and D of the cross-river roads were analyzed. The dynamic characteristics of the traffic volume, probability betweenness centrality, and volume betweenness centrality for these sections are shown in Figure 7.

The traffic status of the sections can be classified with the variation tendency of the indicators in the dynamic analysis from Figure 7. Therein, section A showed a slight decrease in probability betweenness centrality and an increase in volume betweenness centrality, indicating the increase in congestion but still in the acceptable range for the users. Moreover, section B experienced the decrease of both the probability and volume betweenness centrality, indicating congestion and out of the acceptable range for the users and the connectivity of the section is decreasing. Conversely, section D had an increase in both indicators and the connectivity of the section is increasing, indicating there is no serious congestion.

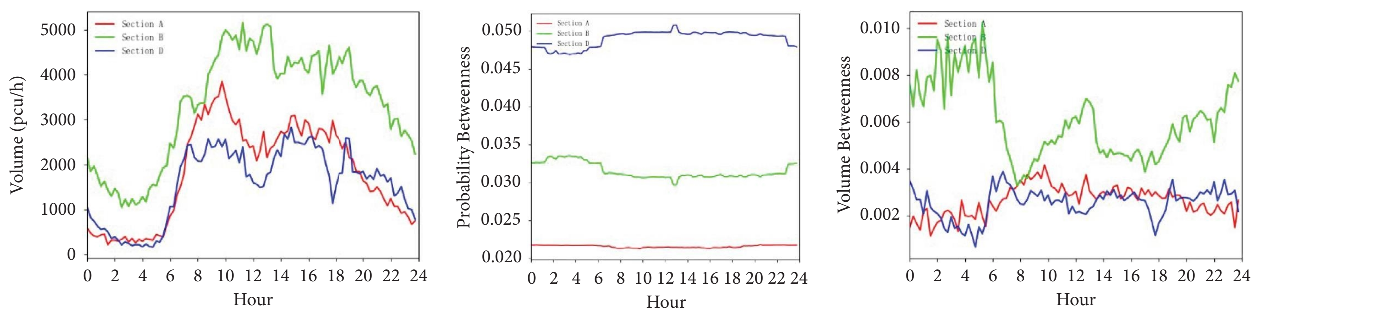
4.4. Imbalance Analysis. This study evaluates the network imbalance with the probability betweenness centrality that involves the road structure and traffic. In the static imbalance analysis, the road structure is considered, while in the dynamic imbalance analysis, the effect of the traffic is taken into account.

4.4.1. Static Imbalance Analysis. The impacts of new sections that contain the imbalance of the cross-river roads and the network are evaluated in the static imbalance analysis. The probability betweenness centrality is adopted as the indicator for assessing the static imbalance of network with new sections. The values of the entropy and Gini coefficient of the probability betweenness centrality are presented in Tables 6 and 7, respectively.

In Table 6, significantly increased 40.23% was observed on the entropy of the cross-river roads with new sections compared with the cross-river roads without new sections and that indicates an improvement in the road structure of the cross-river roads. While, due to the high traffic capacity of section C, the Gini coefficient increased by 3.24%, and

Table 5: Probability betweenness centrality and volume betweenness centrality.

Sections	vb_{i_b} (existing)	pb_{i_b} (existing)	pb_{i_a} (future)
A	0.0032	0.0211	0.0228
B	0.0047	0.0331	0.0086
C	—	—	0.0433
D	0.0024	0.0478	0.0196
E	—	—	0.0126
F	—	0.0026	0.0026



(a) (b) (c)

Figure 7: Dynamic characteristics of sections A, B, and D in the existing network. (a) Traffic volume. (b) Probability betweenness centrality. (c) Volume betweenness centrality.

Table 6: The imbalance of the cross-river roads.

	Cross-river roads (ABDF)	Cross-river roads (ABCDEF)	Changes
Entropy	1.1367	1.539	+40.23%
Gini coefficient	0.3528	0.3852	+3.24%

Table 7: The imbalance of the existing and future networks.

	Existing network	Future network	Changes
Entropy	7.1751	7.1900	+0.21%
Gini coefficient	0.4675	0.4592	−1.78%

there are some efficient policies which can be considered for decreasing the Gini coefficient, such as restricting vehicle entry and raising tolls. Furthermore, the entropy and Gini coefficient remain basically unchanged for the existing and future networks as in Table 7, indicating that no impact of the new sections on the network imbalance was demonstrated in the presented evaluation.

4.4.2. Dynamic Imbalance Analysis. The impact of dynamic traffic volume on the imbalance of the network is investigated. The analysis of the imbalance is performed separately for the cross-river roads and the existing network. The results are presented in Figure 8.

Our investigation reveals an inverse relationship between the entropy and Gini coefficient in dynamic imbalance analysis. A higher entropy value corresponds to a lower Gini coefficient, and conversely, as depicted in Figure 8. As the traffic volume grows, the entropy decreases and the Gini coefficient increases for the cross-river roads, indicating increased imbalance in this context. In contrast, the entropy value increases as the Gini coefficient decreases for the overall network, signifying a reduction in imbalance across the entire network. As can be seen, the imbalance of the cross-river roads should get more attention during traffic peak hours and not the overall network.

4.5. Discussion. An initial objective of the new section project was to identify its feasibility. In the context of redistributing traffic assignment due to the integration of new sections into the existing road network, it is imperative to assess the influence of these new sections on both the network itself and the associated sections. In the present investigation, we conducted evaluations with a focus on connectivity and imbalance, using the metrics of probability betweenness centrality and volume betweenness centrality, which respectively signify traffic supply and demand. These evaluations are expected to serve as valuable tools for the optimization of various parameters related to new sections,

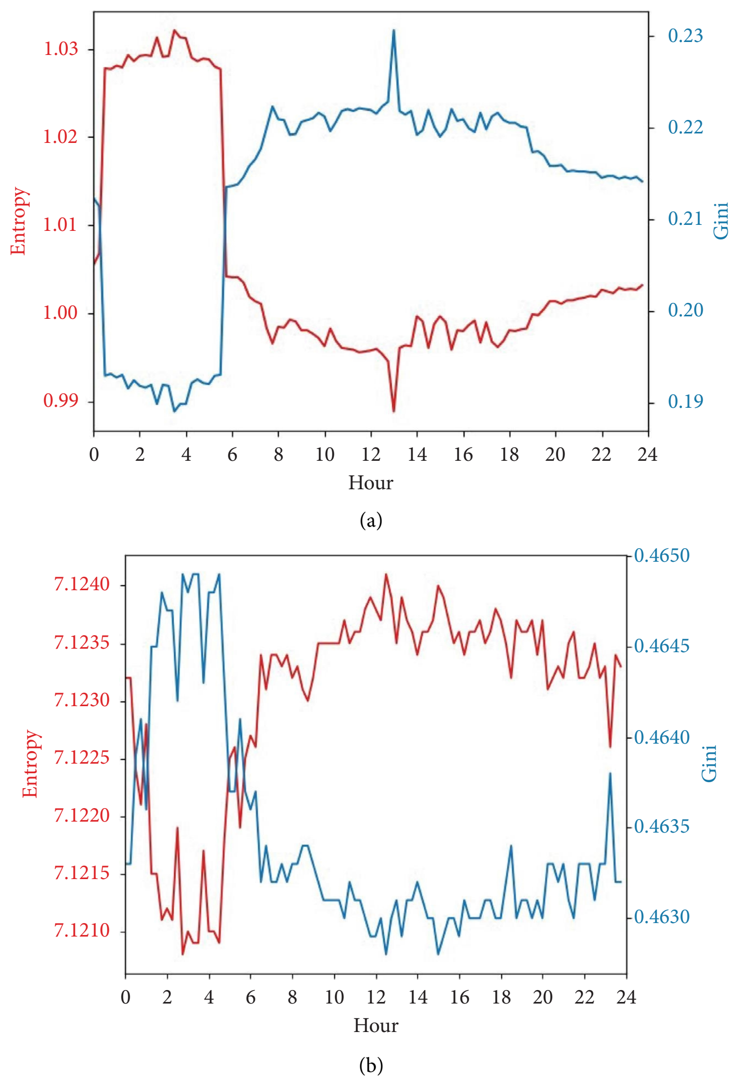


Figure 8: Dynamic characteristics of the imbalance with probability betweenness centrality. (a) The cross-river roads. (b) The existing network.

such as lane configurations, speed limits, and geographic placements. Consequently, these findings are poised to enhance the overall efficacy of feasibility studies.

Connectivity within a transportation network is intricately linked to the physical structure of roads and the volume of traffic they accommodate [15, 25]. To evaluate the extent of the contribution to connectivity, we conducted the comprehensive analysis of both the new sections and their interconnected counterparts in the network, and this analysis hinged on the principles of probability betweenness centrality and volume betweenness centrality grounded in the domain of the complex network theory. In addition, we performed the imbalance analysis, employing a dual eigenvalue approach, to evaluate the imbalance with the entropy and Gini coefficient; this composite index was devised to address the limitations of individual metrics.

Drawing upon these meticulously devised metrics, we formulated the evaluation model within the framework of the complex network theory. The present results are significant in at least three major respects. First, the quantification of the influence of new sections on the connectivity and imbalance of parallel sections is achieved through the innovative utilization of probability betweenness centrality and volume betweenness centrality which are rooted in traffic supply and demand considerations. This approach introduces a supplementary means for enhancing feasibility studies and provides a pathway to expedite and refine assessments. Second, the dynamic interaction between these two betweenness centrality metrics affords insight into the traffic state of road sections and their temporal behavior. Third, the combination of the entropy and Gini coefficient for measuring imbalance demonstrates enhanced precision in the imbalance of the parallel sections and the network, thereby establishing a robust theoretical foundation for efficient traffic management strategies.

In keeping with prior research, our study underscores the significance of comprehensive impact analyses pertaining to new road sections, encompassing connectivity and imbalance evaluations focusing on traffic supply and demand. Notably, the adoption of complex network-based models facilitates more expeditious analyses. Nonetheless, certain limitations warrant acknowledgment. First, the challenges associated with data collection and processing are pronounced, particularly in regard to traffic data, where data quality and its potential impacts on the model's results require further investigation. Second, the treatment of specialized road sections, including those with restrictions on heavy vehicles, presents a distinctive challenge; accordingly, the model calls for refinement, possibly through the vehicle type classifications in the eigenvalue calculations as a viable solution to this issue.

5. Conclusion and Future Directions

This is important for evaluating the impact of new sections because the connectivity and imbalance contribution of new sections can be predicted in the feasibility study; thus, designed guidance can be provided to generate more accurate road design parameters, such as lane number, speed limit, and location. This study presents the evaluation model of new sections based on complex networks, focusing on the connectivity and imbalance contribution of new sections; the model can be used as the supplementary approach for the feasibility study of new highway. The model comprises three modules, i.e., complex network, eigenvalue, and evaluation. In "complex network," the multilayer complex network has been established that provides multiple attributes of sections and incorporates the dynamic edge weight for accurately calculating the transportation costs; meanwhile, the dynamic weight is the foundation of dynamic analysis. In "eigenvalue," probability betweenness centrality and volume betweenness centrality have been established which represent the attribution of sections on traffic supply and demand, respectively. Therein, the MNL model is adopted for the traffic assignment for the probability betweenness centrality and the benefit is that it is consistent with the actual routing selection almost. In "evaluation," on one hand, the connectivity evaluation of road sections is based on probability and volume betweenness centrality. The case study is conducted with the highway network in the Greater Bay Area to validate the evaluation model. The result shows that the new sections are effective in sharing the traffic pressure of sections B and D by 65.1%, and the status of traffic in sections can be judged by the dynamic analysis; On the other hand, the imbalance evaluation is based on the combination of the entropy and Gini coefficient. By adding the new sections C and E, the entropy of the probability betweenness centrality on the cross-river roads increases by 40.23%, indicating an improvement in its structure, while the Gini coefficient increases by 3.24% for the high traffic capacity of section C; meanwhile, the imbalance analysis shows that local sections should be given more attention during traffic peak hours rather than the overall network. To summarize, by evaluating the connectivity and imbalance contribution of new sections, the results of the model can provide guidance for feasibility study of new road sections.

In the further research, it is anticipated that the changes of the road structure will lead to different traffic assignments, and in order to improve the accuracy of connectivity and imbalance analysis, it is necessary that traffic demand prediction should be employed for traffic properties analysis.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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