IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received October 15, 2021, accepted November 30, 2021, date of publication December 1, 2021, date of current version December 21, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3132169

Comprehensive Evaluation of Urban Integrated Transportation Network With Multivariate Statistical Analysis: A Case Study of Haimen

CHANGJIANG ZHENG[1], YUHANG GU[1], JINXING SHEN[1], MUQING DU[1], GENGHUA MA[2], AND KAI SUN[1]
[1]College of Civil and Transportation Engineering, Hohai University, Nanjing 210098, China
[2]College of Harbour, Coastal and Offshore Engineering, Hohai University, Nanjing 210098, China

Corresponding author: Changjiang Zheng (zheng@hhu.edu.cn)

This work was supported in part by the Jiangsu Transportation Science and Technology Project (2021G09).

ABSTRACT This paper proposed a comprehensive evaluation (CE) framework concerning multivariate statistical analysis to provide a systematic assessment and a hierarchical analysis for the urban integrated transportation network (UITN). Specifically, this research contributed the following technical approaches: Firstly, 4 criteria (scale, structure, level of service (LOS), layout) was adopted and indexes were screened from heterogeneous aspects to establish the hierarchical model using correlation coefficient method (CCM). Built upon that, fuzzy comprehensive evaluation method (FCEM) and linear dimensionless (LD) were applied to quantify and nondimensionalize the qualitative and quantitative indexes. In order to improve accuracy and guarantee rationality, this paper then integrated analytic hierarchy process (AHP) with entropy weight method (EWM) to get the index weight. At last, the combination of value analysis (VA) and grey relational analysis (GRA) was used to calculate the CE value. The experimental study shows that our introduced CE framework can offer a thorough evaluation of the UITN, the CE value of UITN in Haimen city is 0.740 and its grade level is ''Medium''. Pros and cons of the structural layout of each transport mode can also be judged through the hierarchical analysis of different indexes. In view of this, corresponding suggestions were given for future improved transportation planning.

INDEX TERMS AHP, CE, GRA, hierarchical analysis, multivariate statistical analysis, UITN.

I. INTRODUCTION

As the significant branch of the urban transportation system, the development of UITN greatly prompts the social progress. However, with the growth of urbanization, the contradiction between the UITN planning and the increasing demand has become distinctive, negatively interfering the socioeconomic growth. Related studies suggest that in order to address the urban transport problems while coordinate the relationship between UITN construction and social progress, it is obligatory to investigate the impacts of related influence factors, with which to reasonably plan the UITN and pilot the limpid development direction [1]–[3].

In recent years, the growing diversification and complexity of transport demand urge a comprehensive and effective transportation planning [4]. As far as it is concerned, as its solid basis, a comprehensive transportation evaluation incorporating multiple layers (highway, railway, waterway, airway *et al.*) is essential [5]. In fact, researchers and engineers have addressed this issue both theoretically and empirically. However, in related studies, the investigation of land transport accounts for the vast majority [6]–[8] and that of the other transport modes was quite roughly mentioned and assessed.

During the planning process, the notion of UITN was raised and studied [9]. The fully development of UITN can provide powerful support for building nation's strength in transport [10] and is considered to be the pioneer of economic growth [11] since it can improve regional accessibility. In studies of assessing transportation network, accessibility was assumed as the indicator [12], [13] and it is found that its influence degree is varied for regions of different sizes

The associate editor coordinating the review of this manuscript and approving it for publication was Roberto Sacile.

(national and continental), with which the regional economic growth can also be predicted. However, the previous studies are mainly confined in one transport mode (especially in highway or railway network) [14], [15]. The characteristics of different transport modes should be notified and highlighted and the spatiotemporal effects should be assessed in a more integrated network [16]. Meanwhile, with the rapid growth of social economy, residents' travel pattern becomes more diversified, which imposes great pressure on the transportation system operation. The complex population structure and their accordingly varied travel behavior require the transformation of UITN [17], [18]. Therefore, in order to clarify how its development can provide satisfactory transport service, it is necessary to incorporate the influence of population in the CE framework [19].

Scholars have designed the quality ranking methodology to analyze the variables and criteria adopted in transportation network evaluation [20]–[22]. In their studies, they pointed that the homogeneity and suitability of the selected variables are rather important for building the evaluation system and environmental and aesthetic impacts were presumed as the significant indexes for assessing transport projects [23]. Though the formulated plans were specifically evaluated and the results were reasonable, it is notable that the environmental and landscape factors they laid great importance on are not the only considerations. The aim of their studies is either achieving sustainability or emphasizing economic benefits [24], which is far from enough to meet the needs of the society. The transportation network system needs the CE, which should incorporate heterogeneous evaluation aspects [25]. In addition, it should also be emphasized that little attention has hitherto been paid to the operation mechanism inside the UITN and a unified and standardized measure that can quantitively and systematically assess the UITN is not built yet.

Varying from single index evaluation, CE provides a systematic and standardized method integrating qualitative and quantitative indexes for evaluating multiple units at the same time. It can comprehensively judge the overall state of the research object and its complex mechanism can be investigated by hierarchical analysis. For cities with multiple transport modes, the CE system of UITN should reflect the real situation and the coordination degree among social, transport and geographical conditions.

Scale and structure [26] are major influence factors of CE system because they are the objective reflection of the components of UITN. In addition to that, the social contentment of the quality of transport operation can be judged from the LOS [27], so it should as well be considered. Besides, the network layout was defined as the coupling and coordination degree of capacity and demand [28], as the core of regional UITN planning, it is also an indispensable part of the CE system.

Enormous studies on the methodology of establishing the UITN evaluation framework have emerged in recent years. Data Envelopment Analysis (DEA) as an evaluation method based on convex analysis and linear programming is widely adopted in the mathematical evaluation model. Although it can calculate the output value accurately, the concept of infinitesimal that is extremely computational intensive [29], [30] needs to be introduced in the process of programming. In contrast, FCEM is easier to implement and suitable to multi-factor and multi-level problems [31], so in this paper, FCEM and LD are adopted to quantify and nondimensionalize the qualitative and quantitative indexes respectively. AHP can integrate relevant elements to establish a hierarchical model and use less quantitative information to program the thinking process of decision-making. For its concise concept and procedures, it is usually combined with other methods to deal with evaluation problems and verified practical [32]–[34]. In this paper, AHP is integrated with EWM [35] to calculate the CE index weight, with which the accuracy can be improved. GRA can determine the development trend of the system affected by the coordinated action of multiple factors, which is also able to determine each factor's influence degree. The spotlight of this method is that the results obtained fit that of the qualitative analysis [36]–[38]. Therefore, after obtaining the index weights, GRA and VA [39] are combined to establish the CE model.

It can be drawn that enormous researches about the transportation network evaluation focus on the unimodal (land transport), instead few can evaluate from an integrated perspective (as shown in FIGURE 1). Comprehensive and detailed evaluation should not ignore multi-layer nature of UITN and the result of evaluation is affected by the synergism of various factors.

CE has been applied in various fields [40]–[42], for transportation planning, it can form a holistic evaluation of the UITN and carry out hierarchical analysis of each index. Besides, in previous studies, the fitness between the qualitative and quantitative indexes is not yet been discussed and few introduce a standardized measure for realizing CE.

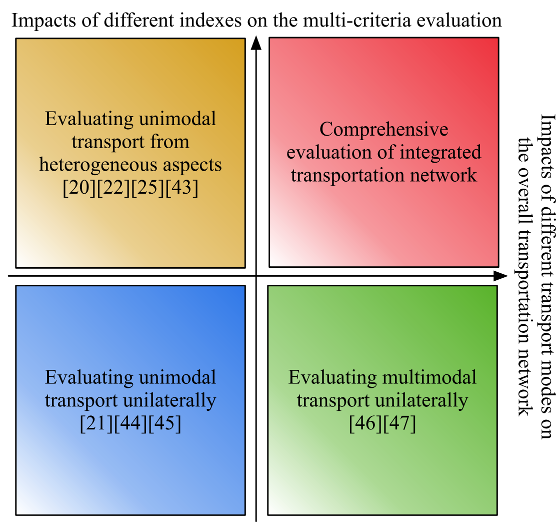

FIGURE 1. Previous studies on transportation network evaluation.

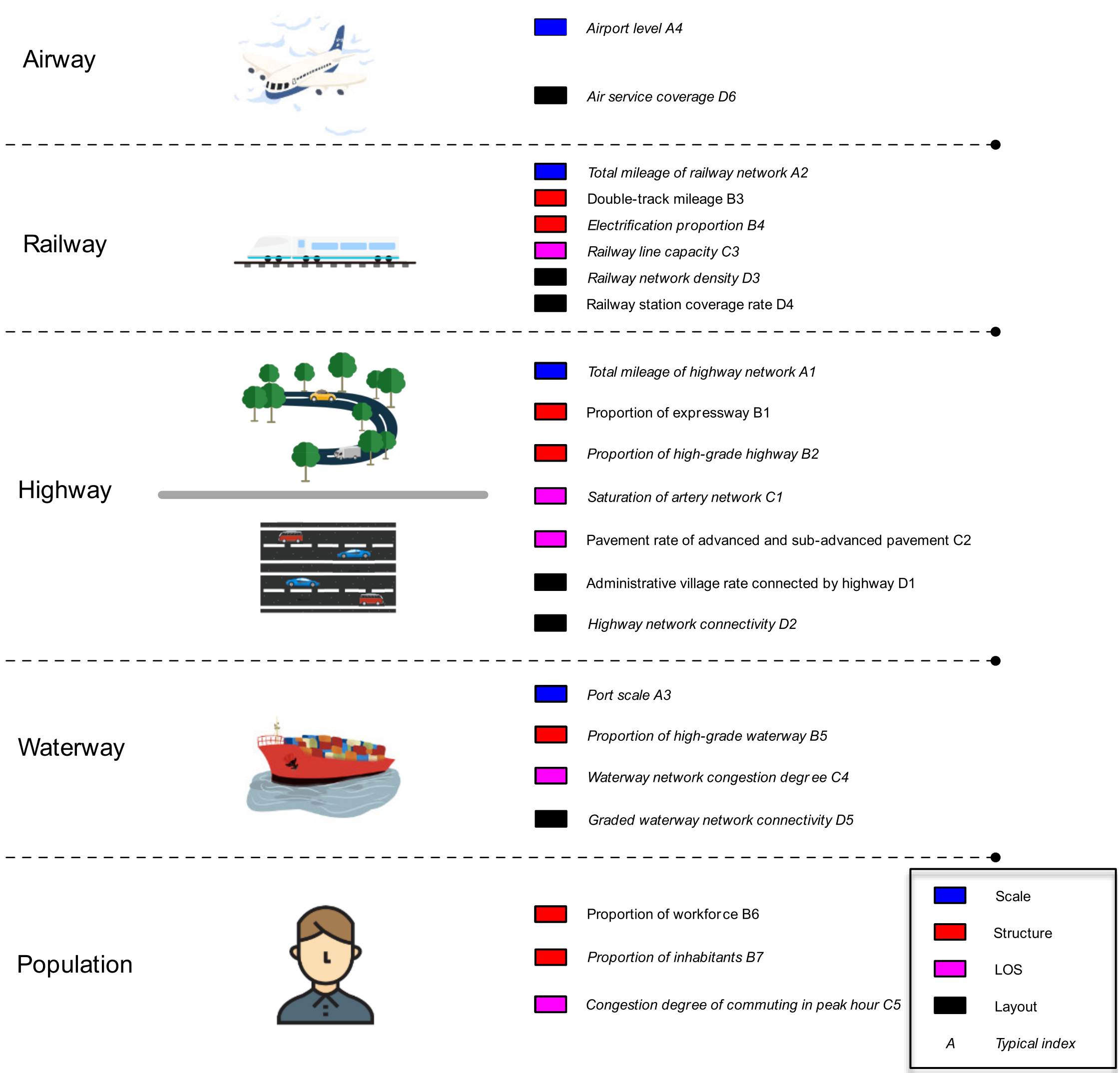

FIGURE 2. CE index system of UITN.

The major contributions of this paper are summarized as follows:

(1) The indexes were screened to build the evaluation index system and put forward specific methods of determining the CE index value;

(2) AHP and EWM are integrated to determine the index weight, with which the accuracy is improved;

(3) The combination of VA and GRA is used to establish the CE model and calculate the CE value to avoid subjectivity;

(4) The case analysis proves the practicability and feasibility of the proposed model and the effectiveness of the adopted methods. Some reasonable suggestions on the improved planning of UITN in Haimen city were raised for reference.

The rest of the paper is organized as follows. Section 2 introduces the established CE index system and its components. Section 3 formulates the methodology of establishing the CE model. Section 4 presents the case analysis, which was carried out to validate our proposed evaluation framework. Finally, conclusions of this paper and some future research directions are discussed in Section 5.

II. ESTABLISHMENT OF CE INDEX SYSTEM

Based on the previous theoretical and empirical studies, it is determined to divide the preliminary CE indexes into four criteria: scale, structure, LOS and layout, which is shown in TABLE 1.

The objectivity and reliability of the CE results depend on whether the selected indexes are accurate and representative. Because of the multi-layer nature of UITN, there existing various transport modes so the indexes come in great varieties. However, it can be found that some of the indexes can be deduced from the others and some of the contents different indexes reflect overlap. Therefore, this paper adopted the Correlation Coefficient Method (CCM) to analyze and screen the indexes.

TABLE 1. Preliminary ce indexes of UITN.

Target Layer	Criteria Layer	Sub-criteria Layer	Index Layer
Preliminary Evaluation Indexes of UITN	Scale	Highway	Total mileage of highway network
			Mileage of high-grade highway
			Highway network density
		Railway	Total mileage of railway network
			Multiple track mileage
		Waterway	Waterway network density
			Mileage of high-grade waterway
			Port scale
		Airway	Airport level
			Transport volume of airport
			Route mileage
			Number of air-routes
		Population	Total number of population
			Passenger transport volume
	Structure	Highway	Proportion of high-grade highway
			Proportion of Expressway
			Road grade level
		Railway	Electrification proportion
			Double-track mileage
		Waterway	Proportion of high-grade waterway
			Proportion of inland port berths
			Proportion of berths of 10000 tons and above
			Proportion of berths in Coastal Ports
		Airway	Proportion of high-grade Airports
		Population	Proportion of workforce
			Proportion of inhabitants
			Proportion of floating population
			Proportion of the elderly
	LOS	Highway	Saturation of artery network
			Pavement rate of advanced and sub-advanced pavement
			Traffic accident rate
			Road grade level
			Asphalt pavement rate
			Mileage saturation rate
		Railway	Workload of railway station
			Railway line capacity
		Waterway	Port handling capacity
			Waterway network congestion
			Load uniformity of waterway network
		Population	Congestion degree of commuting in peak hours
			Commuting time
			Commuting speed in peak hours
	Layout	Highway	Load uniformity of highway network
			Highway network connectivity
			Administrative village rate through highway
			Highway network accessibility
		Railway	Railway network density
			Railway station coverage
		Waterway	Graded waterway network connectivity
			Grade waterway coverage
		Airway	Air service coverage

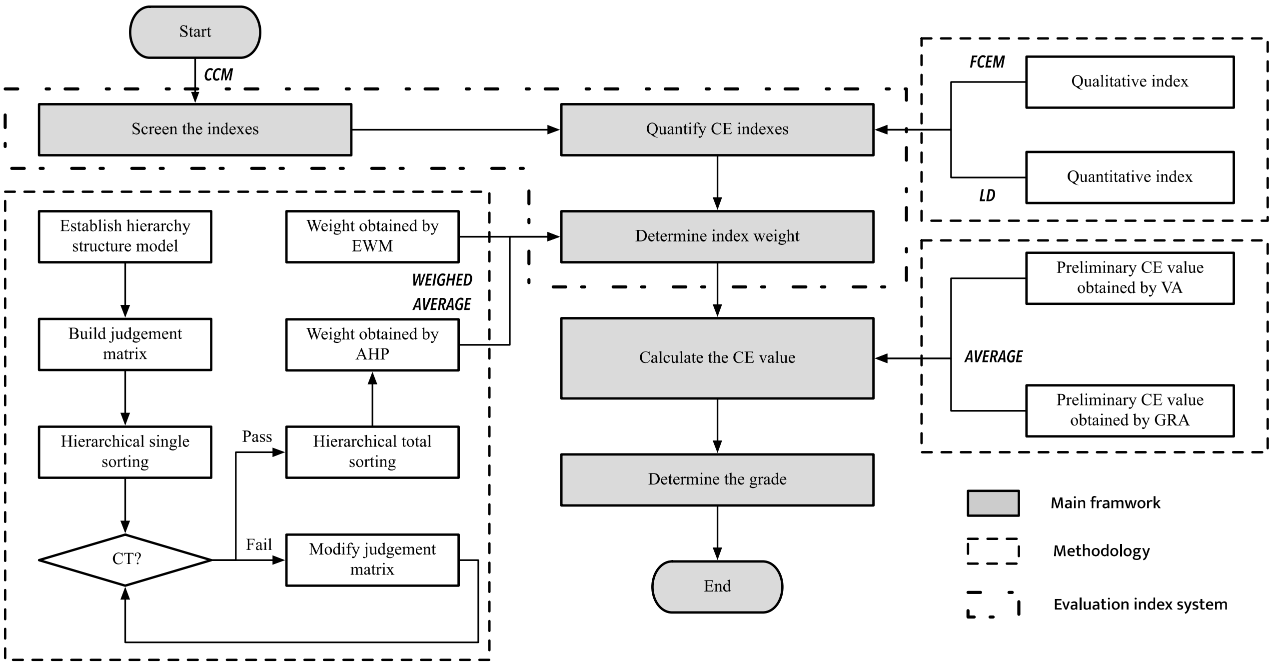

FIGURE 3. **The framework of CE model.**

1) All the indexes have been clustered into 4 criteria, the next step is to choose one as the typical index of each transport mode in each criteria.

(1) Suppose the index set $x = \{$ *Scale, Structure, LOS, Layout* $\}$, X_{yzk} represents the k_{th} index of the z_{th} mode in the y_{th} criteria in TABLE 1. For example, when $y = 2$, $z = 2, k = 2, X_{222}$ represents the index "Double-track mileage" of "Railway" mode in "Structure" criteria.

(2) Let $X^{(yzk)} = \left\{x^1_{yzk}, x^2_{yzk}, \ldots, x^p_{yzk}, \ldots, x^\tau_{yzk}\right\}$ denote the sample value of the k_{th} index of the z_{th} mode in the y_{th} criteria, τ denotes the number of samples, the correlation coefficient r^{km}_{yz} can be calculated as Eq. (1), shown at the bottom of the page.

(3) Coefficient of determination $\overline{r^2_{yzk}}$ can be calculated as Eq. (2).

$$\overline{r^2_{yzk}} = \frac{1}{\tau_{yz-1}} \cdot \sum_{k=1 \cup k \neq m}^{\tau_{yz}} \left(r^{km}_{yz}\right)^2 \tag{2}$$

(4) Choose $\overline{r^2_{yzk}} = max\left\{\overline{r^2_{yzk}}\right\}$ as the typical index of each transport mode in each criteria.

2) Calculate the correlation coefficient between the indexes and typical indexes. In this paper, the critical value M is 0.6. If $r^{k\#}_{yz} \geq M$, the k_{th} index will be considered being retained; otherwise it will be deleted.

After analyzing and screening the indexes, the CE index system of UITN is shown in FIGURE 2.

Several explanations of CE indexes are as follows:

A. SCALE

1) TOTAL MILEAGE OF HIGHWAY NETWORK A1

The total mileage of the highway network can reflect the development of the highway network scale and the coordination degree between the urban economy and the overall transportation system. In this paper, the Connectivity Method (CM) and the Territory Coefficient Method (TCM) are used to calculate the total mileage of highway network, and then the average value is taken as the standard value.

$$A^1_1 = D_N \cdot \xi \cdot \sqrt{R \cdot S} \tag{3}$$

$$A^2_1 = K \cdot \sqrt{P \cdot S} \tag{4}$$

The basic formula of the CM can be expressed as Eq. (3), where A^1_1 is the total mileage of the highway network (km); D_N is the connectivity; S is the total area of the city (km^2); R is the number of connected nodes in this region; ξ is the deformation coefficient of the highway network.

The basic formula of the TCM can be expressed as Eq. (4), where A^2_1 is the total mileage of the highway network (km); K is the coefficient of the urban highway network; P is the total population of the city (10,000 people).

$$r^{km}_{yz} = \frac{\tau \cdot \sum_p \left(x^p_{yzk} \cdot x^p_{yzm}\right) - \sum_p x^p_{yzk} \cdot \sum_p x^p_{yzm}}{\sqrt{\left[\tau \cdot \sum_p \left(x^p_{yzk}\right)^2 - \left(\sum_p x^p_{yzk}\right)^2\right] \cdot \left[\tau \cdot \sum_p \left(x^p_{yzm}\right)^2 - \left(\sum_p x^p_{yzm}\right)^2\right]}} \tag{1}$$

2) Total mileage of railway network A2

$$A2 = C \cdot \sqrt{S \cdot T} \tag{5}$$

In Eq. (5), $A2$ is the scale of the railway network (km); T is the number of important towns; C is the connection coefficient.

B. STRUCTURE

1) PROPORTION OF EXPRESSWAY B1

The standard value of the expressway proportion is obtained by the analogy analysis (AA).

2) ELECTRIFICATION PROPORTION B4

The proportion of electrification in the railway network is directly proportional to the socioeconomic development of the city.

C. LOS

1) SATURATION OF ARTERY NETWORK C1

The saturation of artery network can reflect the demand adaptability of the highway network and the degree of congestion. The evaluation standard adopted in this paper is shown in TABLE 2.

TABLE 2. The evaluation standard of the saturation of artery network.

V/C	Service level
≤0.7	Excellent
(0.7, 0.8]	Better
(0.8, 0.9]	Good
(0.9, 1.0)	Poor
≥1.0	Very bad

2) WATERWAY NETWORK CONGESTION DEGREE C4

The congestion degree of waterway network δ can reflect the operation condition of waterway network.

$$\delta = \frac{M}{Q} = \sum\nolimits_{i=1}^{m} M_i \cdot K_i / \sum\nolimits_{i=1}^{m} M_i \cdot Q_i \tag{6}$$

In Eq. (6), δ is the congestion degree of waterway network; M_i is the mileage per waterway (km); K_i is the planned traffic volume per waterway; Q_i is the capacity per waterway.

D. LAYOUT

1) ADMINISTRATIVE VILLAGE RATE CONNECTED BY HIGHWAY D1

With implementation of rural revitalization strategy, there should be roads connecting cities and villages. Roads connecting administrative villages can drive the economic development of regions along the route and facilitate the development of urban-rural integration.

2) RAILWAY NETWORK DENSITY D3

This paper uses the proportion of operating railway mileage per 100 m^2 as an indicator to evaluate the rationality of the railway network layout. In this paper, the standard value of the railway network density is determined by AA.

3) RAILWAY STATION COVERAGE RATE D4

Rail travel has the advantages of punctuality, high-speed, comfort and safety, so more and more tourists prefer to travel by rail. High accessibility can bring about the boom of economy [48], thus the coverage of railway station is particularly prominent.

4) GRADED WATERWAY NETWORK CONNECTIVITY D5

Graded waterway network connectivity can reflect the characteristics of the layout of the waterway network by examining the connectivity of the node ports and urban transport hubs.

5) CONGESTION DEGREE OF COMMUTING IN PEAK HOURS C5

Congestion degree of commuting in peak hours can reflect the urban traffic congestion situation. The evaluation standard adopted in this paper is shown in TABLE 3 [49], [50].

TABLE 3. The evaluation standard of the congestion degree of commuting.

Situation	Value range
Unblocked	≤1.5
Slow	(1.50, 1.80)
Congested	[1.80, 2.00)
Severely congested	≥2.00

III. ESTABLISHMENT OF CE MODEL

After obtaining the screened indexes, they are nondimensionalized through dimensionless treatment, after which the evaluation value of each index is obtained. Afterwards, the integration of AHP and EWM is explored to calculate and tune the index weight. Finally, VA and GRA are combined to obtain the CE value and assess the grade level of UITN. The established CE framework is shown in FIGURE 3.

A. DIMENSIONLESS TREATMENT OF CE INDEXES

The ultimate purpose of CE is to integrate the information of multiple indexes describing the studied object to obtain a CE value and then conduct analysis to assess this object as a whole. During the process, the integration should be based on the homogeneity of each CE index. However, specific indexes of the CE index system are often non-homogeneous. On the one hand, the dimension of each index value is varied; on the other hand, because each CE index reflects different criteria of the studied object, so the representation forms of these indexes are different. In this way, these CE indexes values will be different in terms of magnitude.

The homogeneity transformation of the indexes can be solved by dimensionless treatment to convert the actual value of the index into a CE value, the integration of different CE indexes can then be proceeded. The specific methods are as follows:

1) DIMENSIONLESS TREATMENT OF QUALITATIVE INDEXES

This paper uses FCEM to quantify and nondimensionalize the qualitative indexes, the results are obtained through Expert Scoring Method (ESM) and the evaluation standard is shown in TABLE 4.

TABLE 4. The evaluation standard of ESM.

Evaluation results	Value range
Excellent	[0.8, 1.0]
Very good	[0.6, 0.8)
Good	[0.4, 0.6)
Bad	[0.2, 0.4)
Very bad	[0.0, 0.2)

2) DIMENSIONLESS TREATMENT OF QUANTITATIVE INDEXES

This paper uses LD to nondimensionalize the quantitative indexes. Suppose the calculated value of index i is p_i, the upper bound and lower bound of p_i are p_{imax} and p_{imin} respectively, $U_{di}(p_i)$ is the nondimensionalized standard function of the index value p_i of d_i. The dimensionless process is formulated as Eqs. (7)-(10).

(1) Profit index (greater value is better):

$$f_i = U_{di}(p_i) = \begin{cases} 0, & p_i \leq p_{imin} \\ \dfrac{p_i - p_{imin}}{p_{imax} - p_{imin}}, & p_{imin} < p_i < p_{imax} \\ 1, & p_i \geq p_{imax} \end{cases} \tag{7}$$

(2) Cost index (smaller value is better):

$$f_i = U_{di}(p_i) = \begin{cases} 0, & p_i \leq p_{imin} \\ \dfrac{p_{imax} - p_i}{p_{imax} - p_{imin}}, & p_{imin} < p_i < p_{imax} \\ 1, & p_i \geq p_{imax} \end{cases} \tag{8}$$

(3) Interval index (the value within a fixed range is better):

$$f_i = U_{di}(p_i) = \begin{cases} 1 - \dfrac{p_{i1} - p_i}{max\{p_{i1} - p_{imin}, p_{imax} - p_{i2}\}}, & p_i < p_{i1} \\ 1 - \dfrac{p_i - p_{i2}}{max\{p_{i1} - p_{imin}, p_{imax} - p_{i2}\}}, & p_i > p_{i2} \\ 1, & p_{i1} \leq p_i \leq p_{i2} \end{cases} \tag{9}$$

Among them, $[p_{i1}, p_{i2}]$ is the most appropriate value range.

(4) Moderate index (the value closer to the median is better):

$$f_i = U_{di}(x_i) = \begin{cases} 0, & p_i \leq p_{imin} \text{ or } p_i \geq p_{imax} \\ \dfrac{2(p_i - p_{imin})}{p_{imax} + p_{imin}}, & p_{imin} < p_i < (p_{imax} + p_{imin})/2 \\ \dfrac{2(p_{imax} - p_i)}{p_{imax} + p_{imin}}, & (p_{imax} + p_{imin})/2 \leq p_i < p_{imax} \end{cases} \tag{10}$$

B. CALCULATION METHODS OF CE INDEX WEIGHT

Different indexes have varied impacts on the studied object and the determination of their weights reflects their priority and directly affects the CE results. Therefore, weighing treatment is required. In this paper, AHP is utilized to calculate the weights of the indexes and EWM is explored to modify the results. The specific procedures are introduced as follows:

1) CALCULATE THE WEIGHT USING AHP

Step1: Establish the judgment matrix according to the relative importance of each index in each criteria.

Suppose that element N_i in criterion layer N is the upper level of element $G_1, G_2, G_3, \ldots, G_n$ in index layer G, the judgment matrix is constructed as Eq. (11).

$$G = \{g_{ij}\}_{n\times n} = \begin{bmatrix} g_{11} & g_{12} & \cdots & g_{1n} \\ g_{21} & g_{22} & \cdots & g_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ g_{n1} & g_{n2} & \cdots & g_{nn} \end{bmatrix} \tag{11}$$

where g_{ij} is the relative importance of g_i relative to g_j, $g_{ij} > 0$; $g_{ij} = \frac{1}{g_{ji}}$; $g_{ii} = 1$.

When proceeding the relative importance comparation among the indexes, this paper uses the scale of 1-9 to calibrate the relative importance of each index (as shown in TABLE 5).

TABLE 5. The calibration of the relative importance of indexes.

Hierarchy of importance	Quantized value
Equally important	1
Index i is slightly more important than index j	3
Index i is more important than index j	5
Index i is quite important compared to index j	7
Index i is extremely important compared to index j	9
The relative importance between index i and j is set between any two hierarchies	2，4，6，8

Step2: Perform hierarchical single sorting and concordance test (CT).

Calculate the index weight and determine the maximum eigenvalue of the judgment matrix, then conduct the CT.

$$CR = \frac{CI}{RI} \tag{12}$$

TABLE 6. The standard value of RI.

ν	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (13)$$

Eq. (12) indicates the formulation of concordance ratio (CR), if CR < 0.1, the judgement matrix will pass the CT; otherwise the judgement matrix should be modified to reconduct CT until it is passed. The formulation of the concordance index (CI) is given in Eq. (13), where ν denotes the order of the judge matrix. The correspondence between RI and ν is shown in TABLE 6.

Step3: Perform hierarchical total sorting and CT.

Calculate all the index weights from the top to the bottom layer and conduct the CT for total ranking results.

2) MODIFY THE CALCULATED WEIGHT USING EWM

Step1: Suppose the weight obtained by AHP is $\alpha_j = (\alpha_1, \alpha_2, \alpha_3, \ldots, \alpha_m)^{\mathrm{T}}$, then transform the matrix into a standardized matrix.

$$\bar{G} = \{\overline{g_{ij}}\}_{n\times n} = \begin{bmatrix} \overline{g_{11}} & \overline{g_{12}} & \cdots & \overline{g_{1n}} \\ \overline{g_{21}} & \overline{g_{22}} & \cdots & \overline{g_{2n}} \\ \vdots & \vdots & \ddots & \vdots \\ \overline{g_{n1}} & \overline{g_{n2}} & \cdots & \overline{g_{nn}} \end{bmatrix}$$

$$\overline{g_{ij}} = g_{ij} / \sum\nolimits_{i=1}^{n} g_{ij} \quad (14)$$

$$S_j = -(\ln n)^{-1} / \sum\nolimits_{i=1}^{n} g_{ij} \cdot \ln g_{ij} \quad \left(0 \le S_j \le 1\right) \quad (15)$$

$$p_j = 1 - S_j \quad (16)$$

Eqs. (15) and (16) denote the formulations of entropy of the index $j(S_j)$ and the deviation degree (P_j).

Step2: Calculate the correction coefficient μ_j.

$$\mu_j = p_j / \sum_{j=1}^{m} p_j \quad (17)$$

$$\alpha_j^{\#} = \mu_j \cdot \alpha_j / \sum\nolimits_{j=1}^{m} \mu_j \cdot \alpha_j \quad (18)$$

The correction coefficient μ_j obtained by Eq. (17) is used to revise the index weight $\alpha_j = (\alpha_1, \alpha_2, \alpha_3, \ldots, \alpha_m)^{\mathrm{T}}$ got from AHP. In Eq. (18), $\alpha_j^{\#}$ is the revised weight of index j.

3) Calculate the final weight of each index.

$$w_j = \theta \cdot \alpha_j + (1 - \theta) \cdot \alpha_j^{\#} \quad (19)$$

Eq. (19) represents that the initial weight obtained by AHP and the modified weight obtained by EWM are weighed to get the final weight of each index, where θ is usually 0.5.

The results of the index weights are shown in TABLE 7- TABLE 8, where $\surd$ indicates CT is passed; otherwise $\times$ is shown.

The hierarchical total ranking CT is conducted as follows: CI = 0.0385, RI = 1.0893, CR = 0.0354 < 0.1, so CT is passed.

TABLE 7. Judgement matrix: criteria layer.

	Scale	Structure	LOS	Layout	Weight
Scale	1	2	3	3	0.4554
Structure	1/2	1	2	2	0.2628
LOS	1/3	1/2	1	1	0.1409
Layout	1/3	1/2	1	1	0.1409
λ_{max}=4.0104	CI=0.0035	RI=0.90	CR=0.0038		√

TABLE 8. Judgement matrix: scale, structure, los and layout.

Scale	A1	A2	A3	A4	Weight
A1	1	2	2	2	0.3880
A2	1/2	1	3	3	0.3298
A3	1/2	1/3	1	1	0.1411
A4	1/2	1/3	1	1	0.1411
λ_{max}=4.1545	CI=0.0515	RI=0.90	CR=0.0572		√

Structure	B1	B2	B3	B4	B5	B6	B7	Weight
B1	1	1	1	2	2	1/2	1/2	0.1231
B2	1	1	1	3	3	1/2	1/2	0.14
B3	1	1	1	2	2	1/3	1/3	0.1111
B4	1/2	1/3	1/2	1	1	1/4	1/3	0.0611
B5	1/2	1/3	1/2	1	1	1/4	1/4	0.0582
B6	2	2	3	4	4	1	1	0.2619
B7	2	2	3	2	4	1	1	0.2446
λ_{max}=7.0373	CI=0.0062		RI=1.32		CR=0.0047			√

LOS	C1	C2	C3	C4	C5	Weight
C1	1	1/2	1/2	2	1/3	0.1209
C2	2	1	1	3	1/2	0.2147
C3	2	1	1	3	1/2	0.2147
C4	1/2	1/3	1/3	1	1/4	0.0738
C5	3	2	2	4	1	0.376
λ_{max}=5.0331	CI=0.0083	RI=1.12	CR=0.0074			√

Layout	D1	D2	D3	D4	D5	D6	Weight
D1	1	3	4	2	6	8	0.3833
D2	1/3	1	3	4	6	8	0.2822
D3	1/4	1/3	1	1	4	6	0.1215
D4	1/2	1/4	1	1	6	6	0.1453
D5	1/6	1/6	1/4	1/6	1	2	0.0405
D6	1/8	1/8	1/6	1/6	1/2	1	0.0272
λ_{max}=6.4353	CI=0.0871		RI=1.24	CR=0.0702			√

Then EWM is explored to obtain the revised weight $\alpha_j^{\#}$, the detailed information is shown in TABLE 9.

The initial weight obtained by AHP and the modified weight obtained by EWM are weighed and calculated by Eq. (19) to obtain the final weight, the result of each index weight in each criteria is shown in FIGURE 4.

C. CALCULATION METHODS OF CE VALUE

In this paper, in order to eliminate the subjectivity of employing only one method, the combination of VA and GRA is

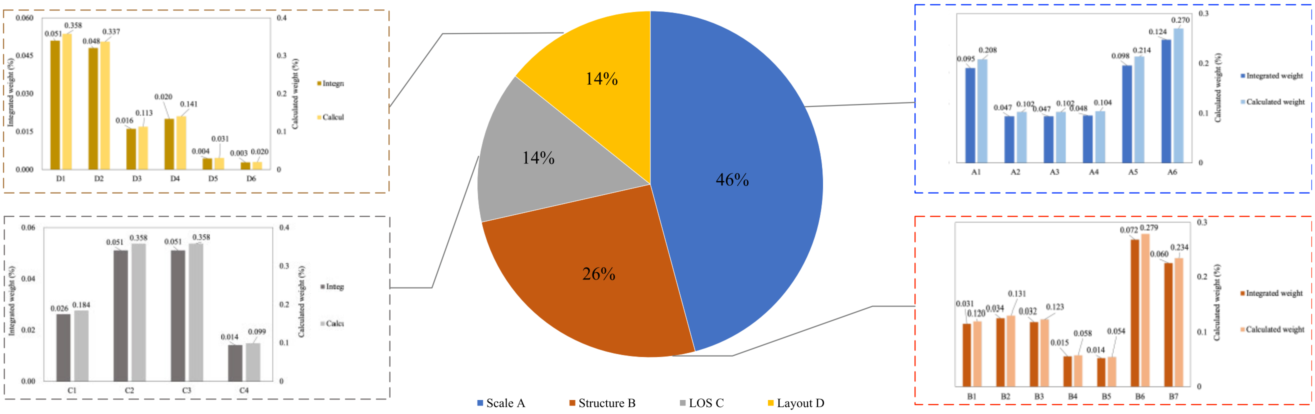

FIGURE 4. The diagram of the CE index weight.

TABLE 9. The detailed information of the revised weight.

	Index	S_j	P_j	μ_j	$\alpha_j^{\#}$
Criteria	Scale	0.3779	0.6221	0.2758	0.4616
	Structure	0.4212	0.5788	0.2566	0.2502
	LOS	0.4728	0.5272	0.2338	0.1441
	Layout	0.4728	0.5272	0.2338	0.1441
Scale	A1	0.0311	0.9689	0.3760	0.5315
	A2	0.4462	0.5538	0.2149	0.2582
	A3	0.4728	0.5272	0.2046	0.1052
	A4	0.4728	0.5272	0.2046	0.1052
Structure	B1	0.7556	0.2444	0.1387	0.1170
	B2	0.7769	0.2231	0.1266	0.1214
	B3	0.6855	0.3145	0.1785	0.1359
	B4	0.7709	0.2291	0.1300	0.0544
	B5	0.7758	0.2242	0.1272	0.0507
	B6	0.7090	0.2910	0.1652	0.2964
	B7	0.7644	0.2356	0.1337	0.2241
LOS	C1	0.7901	0.2099	0.1691	0.0941
	C2	0.7196	0.2804	0.2259	0.2232
	C3	0.7196	0.2804	0.2259	0.2232
	C4	0.8242	0.1758	0.1416	0.0481
	C5	0.7050	0.2950	0.2376	0.4113
Layout	D1	0.6879	0.3121	0.1716	0.3324
	D2	0.4994	0.5006	0.2753	0.3925
	D3	0.6887	0.3113	0.1712	0.1051
	D4	0.6633	0.3367	0.1851	0.1359
	D5	0.8115	0.1885	0.1036	0.0212
	D6	0.8305	0.1695	0.0932	0.0128

utilized to obtain the CE value. The specific procedures are as follows:

1) CALCULATE THE PRELIMINARY CE VALUE USING VA

$$V = \sum z_i \tag{20}$$

$$Z_i = f_i \cdot w_i \tag{21}$$

Eqs. (20) and (21) indicate the formulations of VA, where V is the preliminary CE value; Z_i is the CE value of index i; f_i is the evaluation value after dimensionless treatment.

2) CALCULATE THE PRELIMINARY CE VALUE USING THE GRA

$$R = E \cdot W \tag{22}$$

$$E = \begin{bmatrix} \xi_{11} & \xi_{12} & \cdots & \xi_{1n} \\ \xi_{21} & \xi_{22} & \cdots & \xi_{2n} \\ \xi_{31} & \xi_{32} & \cdots & \xi_{3n} \\ \vdots & \vdots & \vdots & \vdots \\ \xi_{m1} & \xi_{m2} & \cdots & \xi_{mn} \end{bmatrix} \tag{23}$$

$$W = [w_1 + w_2, w_3 \cdots w_n] \tag{24}$$

Eq. (22) represents the basic formulation of GRA. The correlation coefficient matrix is given in Eq. (23), where ξ_{ij} is the correlation coefficient of the j_{th} index in the i_{th} criteria. Eq. (24) denotes the weights of n indexes, $\sum_{i=1}^{n} w_i = 1$.

Step1: Determine the optimal index set.

Suppose there are n indexes, select the optimal indexes (Eq. (25)).

$$X^* = [X_1^*, X_2^*, X_3^* \cdots] \tag{25}$$

$$D = \begin{bmatrix} x_1^* & x_2^* & \ldots & x_n^* \\ x_{11} & x_{12} & \ldots & x_{1n} \\ \vdots & \vdots & \ldots & \vdots \\ x_{m1} & x_{m2} & \ldots & x_{mn} \end{bmatrix}$$

$$\rightarrow C = \begin{bmatrix} c_1^* & c_2^* & c_3^* & \ldots & c_n^* \\ c_{11} & c_{12} & c_{13} & \ldots & c_{1n} \\ c_{21} & c_{22} & c_{23} & \ldots & c_{2n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ c_{m1} & c_{m2} & c_{m3} & \ldots & c_{mn} \end{bmatrix} \tag{26}$$

In Eq. (26), matrix D is built according to the original data, here the dimensionless treatment is explored to standardize the indexes in matrix D to that in matrix C.

Step2: Calculate the gray correlation coefficient.

Split matrix C, suppose the reference series: $C^* = [c_{10}\ c_{20}\ c_{30}\ \cdots\ c_{n0}]$ and the comparison series: $C = [c_{i1}\ c_{i2}\ c_{i3}\ \ldots\ c_{in}]\quad i = 1, 2, \ldots n$, then calculate the correlation coefficient ξ_{ik} (Eq. (27)), as shown at the bottom of the page. where ρ is the identification coefficient, $p \in [0, 1]$.

Step3: Calculate the preliminary CE value.

$$R = [r_1 \quad r_2 \quad r_3 \quad \ldots \quad r_m] \tag{28}$$

In Eq. (28), according to Eqs. (22)-(24), $r_i = \sum_{k=1}^{n} \xi_{ik} \cdot w_k, i = 1, 2, 3 \ldots m$.

3) Calculate the final CE value.

$$\psi = \frac{V + R}{2} \tag{29}$$

Eq. (29) denotes the formulation of getting the final CE value and the grade of the evaluated UITN can be referred in TABLE 10 [51].

TABLE 10. The grade level of the evaluated UITN.

Grade	CE value
Unqualified	[0.0, 0.6)
Qualified	[0.6, 0.7)
Medium	[0.7,0.8)
Good	[0.8, 0.9)
Excellent	[0.9, 1.0]

IV. IMPLEMENTATION AND ANALYSIS

A. STUDY SITE SELECTION AND DESCRIPTION

The UITN of Haimen is selected as the study scenario to validate the proposed CE model, then corresponding discussions are given through hierarchical analysis.

Haimen city is located at the Yangtze River estuary and close to Shanghai. Benefited from its geographic location, it has rich transport compositions (involve all the 4 modes [52]), as shown in FIGURE 5.

B. RESULTS AND DISCUSSIONS

The preliminary CE values calculated are shown in TABLE 11 and the final CE value obtained is 0.740 (Eq. (29)). By referring TABLE 10, the grade level of UITN in Haimen city is "Medium".

The rapid development of UITN in Haimen has strongly promoted the socioeconomic growth. However, from the perspective of CE and its obtained results, there are still deficiencies. Highway network can strive for further progress and improvement, while the development of railway, waterway and airway is still in a shallow level. The overall transport status of Haimen still lags behind the national average level and there is little possibility for the landing of a comprehensive transport hub in the short run. It can also be drawn that the scale and structure of UITN play a significant role in the CE process (FIGURE 4), so it is particularly important to improve the scale and optimize the structure of the UITN. In addition, the indexes concerning population indicate that with the population growth, the current traffic condition of Haimen is unable to satisfy the surging travel demand and requires evolution. The current status and suggestions for the improved planning of each transport mode can be expounded as follows:

1) HIGHWAY

As shown in FIGURE 6 (a), the total mileage of the highway network is insufficient, which is slightly lower than the lower bound of the national level. Though the highway network connectivity reaches the average level, the proportion of expressway is rather lower (FIGURE 6 (b)). Besides, there are few high-grade highways (mainly 3rd-grade and 4th-grade highways) and the saturation of its artery network is high, these weaknesses result in the low overall accessibility both inside and outside the city. The proportion of different grade highways is unbalanced and not coordinated, which leads to the unreasonable overall layout. Considering the current situation that 1) most of the national and provincial arteries are concentrated in the main city and areas along the Yangtze River; 2) some highway channels overlap seriously; 3) insufficient highway coverage in the northern area of the city, as exhibited in FIGURE 7, it is advised that 4 national and provincial roads be routed and 4 provincial roads be newly upgraded (http://www.jshmzc.com/hmzc/zwzx/content/7bbe7b9f-0a66-45b4-8984-e7d0d9fdd13b.html).

2) RAILWAY

The railway scale of Haimen City is so small. It possesses only one Ningqi Railway and its length is just 38km, no wonder it provides poor railway LOS for its low railway line capacity (FIGURE 6 (c)). The layout is also not perfect, the railway network density is low (FIGURE 6 (d)) so its impact on supporting the development of the overall urban transportation system is quite limited. The function of the railway station should be strengthened as well. At present, for the high-speed rail travel can provide comfortable and reliable service, more and more people tend to choose travelling by rail.

$$\xi_{ik} = \left.\begin{matrix} \dfrac{min_i \cdot min_k \cdot |c_{ok} - c_{ik}| + \rho \cdot max_i \cdot max_k \cdot |c_{ok} - c_{ik}|}{|c_{ok} - c_{ik}| + \rho \cdot max_i \cdot max_k} \\ \Delta min = min_i \cdot min_k \cdot \left|c_k^* - c_{ik}\right| \\ \Delta max = max_i \cdot max_k \cdot \left|c_k^* - c_{ik}\right| \end{matrix}\right\} \rightarrow \xi_{ik} = \frac{\Delta min + \rho \cdot \Delta max}{\left|c_k^* - c_{ik}\right| + \rho \cdot \Delta max} \tag{27}$$

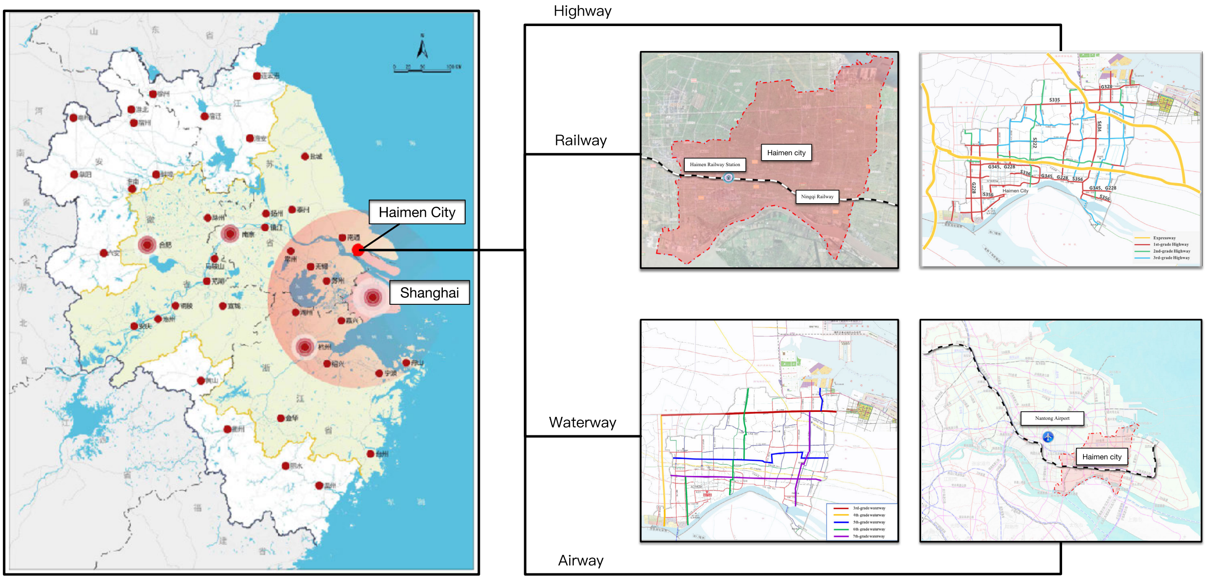

FIGURE 5. Transport compositions of Haimen city.

TABLE 11. Preliminary CE value obtained by VA and GRA.

Criteria	Index	Evaluation value	Dimensionless value	Index weight	Integrated weight	CE value (VA)	GRA		
							Δ	ξ_{ik}	CE value
Scale	A1	2562.8km	0.645	0.460	0.115	0.074	0.355	0.561	0.068
	A2	38km	0.667	0.294	0.073	0.049	0.333	0.577	0.045
	A3	0.9	1.000	0.123	0.031	0.031	0.000	1.000	0.031
	A4	0.7	0.800	0.123	0.031	0.025	0.200	0.694	0.023
Structure	B1	1.58%	0.351	0.120	0.030	0.011	0.649	0.383	0.010
	B2	19.50%	0.975	0.131	0.033	0.032	0.025	0.948	0.028
	B3	100%	1.000	0.123	0.031	0.031	0.000	1.000	0.031
	B4	100%	1.000	0.058	0.014	0.014	0.000	1.000	0.014
	B5	9.07%	0.363	0.054	0.014	0.005	0.637	0.366	0.005
	B6	60.70%	0.767	0.279	0.070	0.054	0.233	0.755	0.051
	B7	63.15%	0.734	0.234	0.059	0.043	0.266	0.732	0.040
LOS	C1	0.74	0.600	0.108	0.027	0.016	0.400	0.532	0.015
	C2	97.80%	1.000	0.219	0.055	0.055	0.000	1.000	0.055
	C3	14	0.583	0.219	0.055	0.032	0.417	0.493	0.030
	C4	0.764	0.860	0.061	0.015	0.013	0.140	0.764	0.012
	C5	1.334	0.666	0.394	0.098	0.066	0.334	0.568	0.062
Layout	D1	100%	1.000	0.358	0.089	0.089	0.000	1.000	0.089
	D2	2.62	0.760	0.337	0.084	0.064	0.240	0.654	0.060
	D3	3.31 km/100 km2	0.735	0.113	0.028	0.021	0.265	0.632	0.019
	D4	65%	0.722	0.141	0.035	0.025	0.278	0.620	0.023
	D5	1.56	0.867	0.031	0.008	0.007	0.133	0.774	0.006
	D6	75%	0.882	0.020	0.005	0.004	0.118	0.794	0.003
Σ		—	—	4	1	0.760	—	—	0.720

However, Haimen Station of Ningqi Railway is of low service level and its functions are imperfect, the freight function of the railway hub has also not been fully utilized, so its layout needs to be further optimized to improve its transport efficiency. As shown in FIGURE 8, it is suggested that a high-speed railway be newly built and Haimen North Railway Station be newly set (https://www.yangtse.com/content/1236900.html) to realize high-speed railway travel

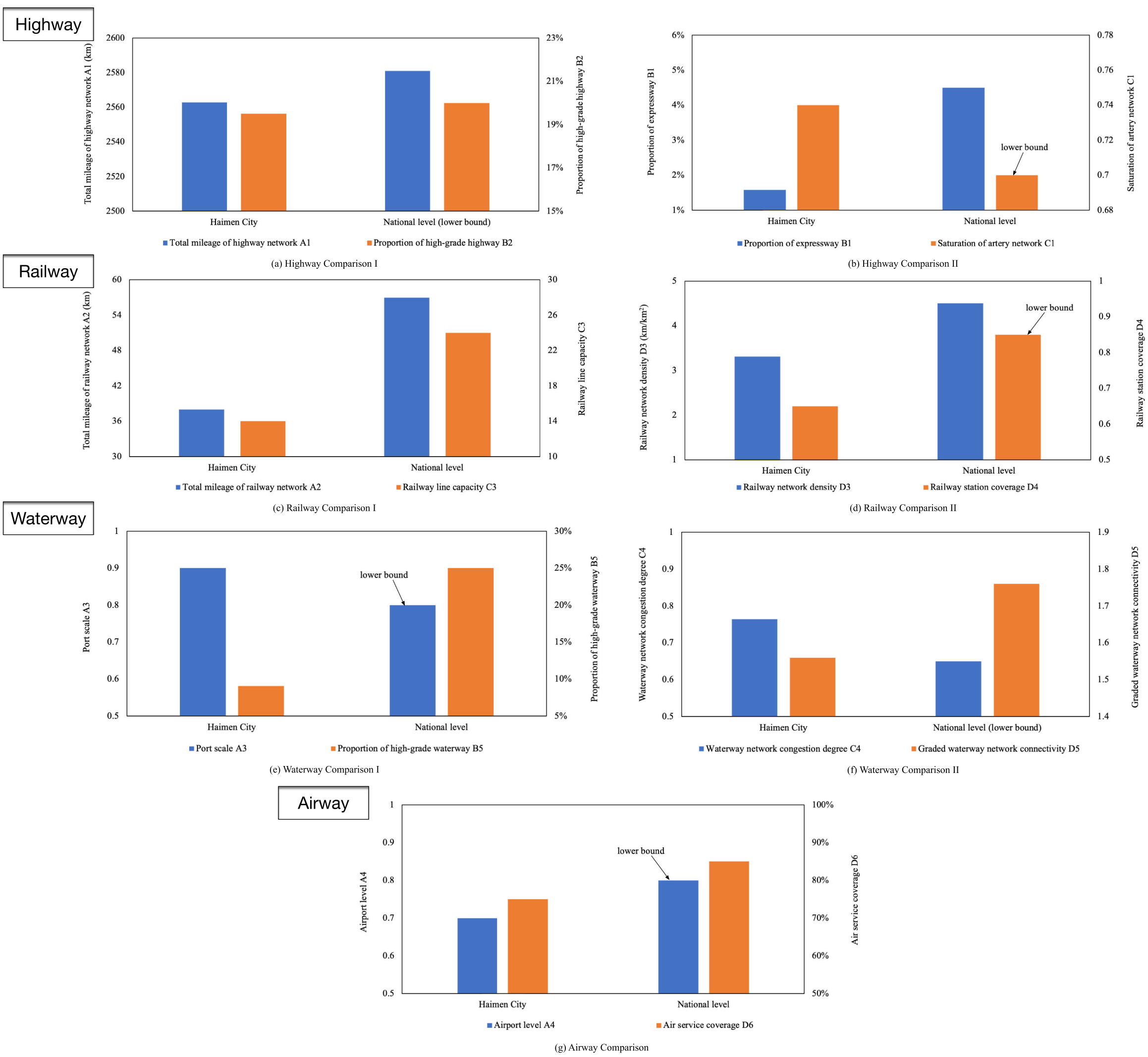

FIGURE 6. **The analysis of current status of UITN in Haimen.**

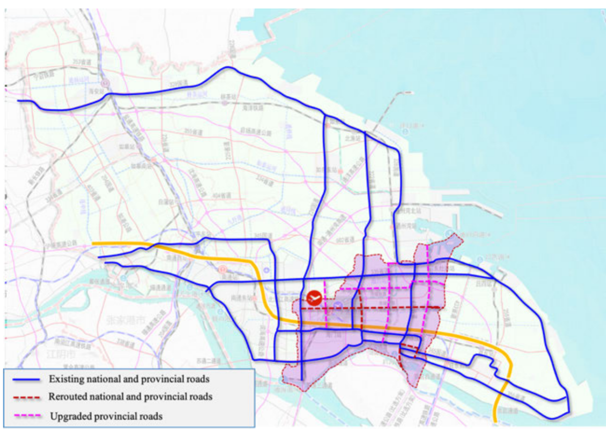

FIGURE 7. **The diagram of suggestions for highway transportation.**

and improve the railway network density and railway station coverage, which further optimize the transport structural layout and improve LOS.

3) WATERWAY

Although the scale of the port reaches the national average level, the cognition of port is vague and its functions are not fully exploited. The proportion of high-grade waterway is quite low (FIGURE 6 (e), FIGURE 9) so its interflow with high-grade ports is rather limited. The waterway network congestion degree goes beyond the upper bound of the standard value (FIGURE 6 (f)), thus low LOS and poor transport efficiency are provided and the advantages of waterway transport can't be given into full play, which strongly restrict its development. In view of this, it is suggested to build a high-quality inland waterway network with the artery of Yangtze River as the core and the 3rd-grade waterways as the framework (as shown in FIGURE 10). The purpose is to connect the sea port and Haimen port with the 3rd-grade waterway channels to strengthen the River-Ocean combined transport (http://jtysj.nantong.gov.cn/ntjy/upload/27d6130b-22f5-4337-b2ce-23ee9d52b523.pdf).

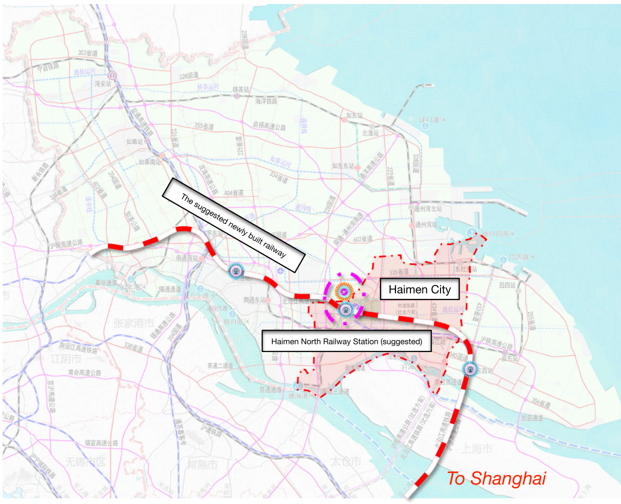

FIGURE 8. The diagram of suggestions for railway transportation.

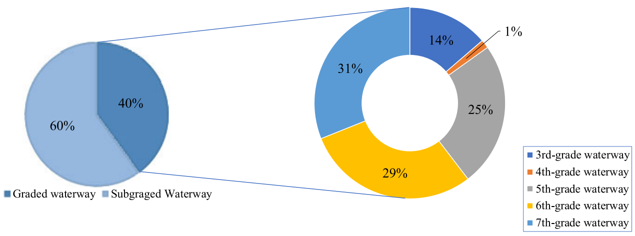

FIGURE 9. The diagram of the compositions of grade waterways.

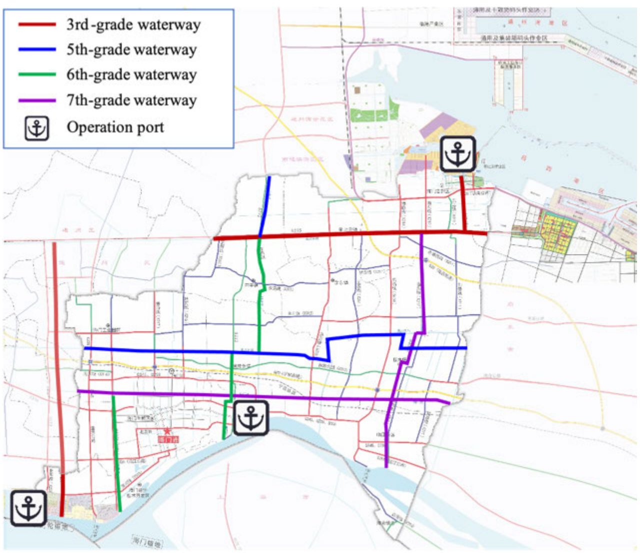

FIGURE 10. The diagram of suggestions for waterway transportation.

4) AIRWAY

Haimen residents mainly used Nantong Xingdong International Airport for travelling while its airway development is lagged behind. As shown in FIGURE 6 (g), the airport has few airlines and flights and small air service coverage. To meet the rapid growth of Haimen economy, in the long run, it is suggested to learn from the construction experience, scale and positioning of Chengdu Tianfu Airport and build a 4F airport in Haimen. Haimen Airport Economic Zone should be recognized as the Regional Aviation Hub and Advanced Aviation Industrial Agglomeration Zone, which takes airway transportation, air logistics and international business as the main development industries (https://www.ettoday.net/news/20190215/1378443.htm).

V. CONCLUSION AND DIRECTIONS FOR FUTURE WORKS

This paper proposed a CE framework to comprehensively evaluate UITN with multivariate statistical analysis. Due to the diversity of the evaluation indexes, 4 criteria was adopted and indexes were screened through CCM. In the next, FCEM and LD were used to quantify and nondimensionalize the qualitative and quantitative indexes. Then the weights of the selected CE indexes are calculated through the integration of AHP and EWM. After obtaining the weights, the CE value was given by the combination of VA and GRA. At last, the case of UITN in Haimen was chosen to apply our established CE model, the results were analyzed and suggestions for the improved UITN planning were raised for reference.

The advancements and innovations are as follows:

1) Our CE model can provide a systematic view of UITN, the CE value can be referred to assess the studied object's general development trend and comprehensive level, based on which the improved decisions can be made.

2) The integration of AHP and EWM can improve the accuracy of the index weight and the subjectivity of employing one approach is avoided through averaging the value of VA and GRA.

3) The established CE framework exhibits adequate practicability and feasibility, it provides a theoretical foundation for partial-global planning and structural layout optimization of UITN.

There are several promising future research directions stemmed from this study. During the process of dimensionless treatment of qualitative indexes, ESM is applied and kind of subjective, so it is the same with the process of determining the weight by applying AHP (ESM). Methods shunning subjectivity in the analysis are few and therefore worth studying. Besides, with the rapid development of the transportation system, pipeline transport has gradually come into practice and is also a significant component of the UITN, the index selection of pipeline transport and its evaluation criteria is also an interesting direction for digging into. Such extensions will make our study more scientific and functional and be addressed in our future works.

REFERENCES

[1] M. Hatzopoulou and E. J. Miller, "Institutional integration for sustainable transportation policy in Canada," *Transp. Policy*, vol. 15, no. 3, pp. 149–162, May 2008.

[2] A. Aloui *et al.*, "Systematic literature review on collaborative sustainable transportation: Overview, analysis and perspectives," *Transp. Res. Interdiscipl. Perspect.*, vol. 9, 2021, Art. no. 100291.

[3] S. Yao and L. Lan, "Research on regional transportation network development strategies based on regional synergy: A case study of Guangdong-Hong Kong-Macao greater bay area," in *Proc. Int. Conf. Smart Veh. Technol., Transp., Commun. Appl.*, 2018, pp. 22–28.

[4] Q. Xiong, J. Hu, and J. Kuai, "Comprehensive transportation corridor layout of urban agglomeration based on improved ant colony algorithm," in *Proc. ICTE*, Jan. 2020, pp. 77–85.

[5] A. Rahimi-Golkhandan and M. J. Garvin, "A socio-economic comparison of urban areas with different transportation system diversity," in *Proc. Construct. Res. Congr., Infrastruct. Syst. Sustainability*. Reston, VA, USA: American Society of Civil Engineers, 2020, pp. 771–780.

[6] J. Zeng and F. Qi, "A comprehensive evaluation model and empirical research on railway freight rates under a competitive environment," *Transp. Res. Rec.*, vol. 2675, no. 12, pp. 929–938, 2021.

[7] W. Li, Q. Luo, J. Zhou, and X. Zhang, "Quantitative modeling and comprehensive evaluation of urban rail transit network dynamic accessibility," in *Proc. 3rd IEEE Int. Conf. Intell. Transp. Eng. (ICITE)*, Sep. 2018, pp. 95–99.

[8] H. Yin, "Evaluation model of urban-rural transportation integration development level," in *Proc. IOP Conf., Mater. Sci. Eng.*, 2019, vol. 688, no. 2, Art. no. 022022.

[9] A. Adamski, "Intelligent integrated transportation systems," in *Proc. 9th Meeting EURO WG Intermodality, Sustainability ITS*, vol. 565, no. 570, Bari, Italy, 2002.

[10] I. H. El-adaway, I. S. Abotaleb, and E. Vechan, "Social network analysis approach for improved transportation planning," *J. Infrastruct. Syst.*, vol. 23, no. 2, Jun. 2017, Art. no. 05016004.

[11] B. Li, S. Gao, Y. Liang, Y. Kang, T. Prestby, Y. Gao, and R. Xiao, "Estimation of regional economic development indicator from transportation network analytics," *Sci. Rep.*, vol. 10, no. 1, pp. 1–15, Dec. 2020.

[12] S. K. Fayyaz, X. C. Liu, and R. J. Porter, "Dynamic transit accessibility and transit gap causality analysis," *J. Transp. Geography*, vol. 59, pp. 27–39, Feb. 2017.

[13] S. Bikdeli, S. Shafaqi, and F. Vosouqi, "Accessibility modeling for land use, population and public transportation in mashhad, NE Iran," *Spatial Inf. Res.*, vol. 25, no. 3, pp. 481–489, Jun. 2017.

[14] P. Kelle, J. Song, M. Jin, H. Schneider, and C. Claypool, "Evaluation of operational and environmental sustainability tradeoffs in multimodal freight transportation planning," *Int. J. Prod. Econ.*, vol. 209, pp. 411–420, Mar. 2019.

[15] Z.-Z. Shao, Z.-J. Ma, J.-B. Sheu, and H. O. Gao, "Evaluation of large-scale transnational high-speed railway construction priority in the belt and road region," *Transp. Res. E, Logistics Transp. Rev.*, vol. 117, pp. 40–57, Sep. 2018.

[16] I. Yatskiv and E. Budilovich, "A comprehensive analysis of the planned multimodal public transportation HUB," *Transp. Res. Proc.*, vol. 24, pp. 50–57, Jan. 2017.

[17] L. Dong, R. Li, J. Zhang, and Z. Di, "Population-weighted efficiency in transportation networks," *Sci. Rep.*, vol. 6, no. 1, p. 26377, Feb. 2016.

[18] F. X. Zhao and H. Y. Shang, "Role of transportation network on population distribution evolution," *Phys. A, Stat. Mech. Appl.*, vol. 577, Sep. 2021, Art. no. 126076.

[19] R. Li, L. Dong, J. Zhang, X. Wang, W.-X. Wang, Z. Di, and H. E. Stanley, "Simple spatial scaling rules behind complex cities," *Nature Commun.*, vol. 8, no. 1, pp. 1–7, Dec. 2017.

[20] A. Salehi, F. H. Lotfi, and M. R. Malkhalifeh, "Evaluation and ranking of rail freight and passenger transportation in same Asian countries with new method in data envelopment analysis," *J. Math. Extension*, vol. 15, pp. 61–92, Sep. 2019.

[21] M. Nassereddine and H. Eskandari, "An integrated MCDM approach to evaluate public transportation systems in Tehran," *Transp. Res. A, Policy Pract.*, vol. 106, pp. 427–439, Dec. 2017.

[22] S. Seker and N. Aydin, "Sustainable public transportation system evaluation: A novel two-stage hybrid method based on IVIF-AHP and CODAS," *Int. J. Fuzzy Syst.*, vol. 22, no. 1, pp. 257–272, Feb. 2020.

[23] D. K. Pathak, L. S. Thakur, and S. Rahman, "Performance evaluation framework for sustainable freight transportation systems," *Int. J. Prod. Res.*, vol. 57, no. 19, pp. 6202–6222, Oct. 2019.

[24] B. Van Wee, R. Van Den Brink, and H. Nijland, "Environmental impacts of high-speed rail links in cost–benefit analyses: A case study of the Dutch Zuider Zee line," *Transp. Res. D, Transp. Environ.*, vol. 8, no. 4, pp. 299–314, 2003.

[25] A. Krapp, J. M. Barajas, and A. Wennink, "Equity-oriented criteria for project prioritization in regional transportation planning," *Transp. Res. Rec., J. Transp. Res. Board*, vol. 2675, no. 9, pp. 182–195, Sep. 2021.

[26] Y. Qiang, G. Tian, Y. Liu, and Z. Li, "Energy-efficiency models of sustainable urban transportation structure optimization," *IEEE Access*, vol. 6, pp. 18192–18199, 2018.

[27] M. Rahimi, A. Baboli, and Y. Rekik, "Multi-objective inventory routing problem: A stochastic model to consider profit, service level and green criteria," *Transp. Res. E, Logistics Transp. Rev.*, vol. 101, pp. 59–83, May 2017.

[28] X. Zhu, X. Feng, L. Zhang, and W. Hua, "Optimizations of network layout and transport service frequencies in view of interests of transit line operators and utilizers," *Arch. Transp.*, vol. 50, no. 2, pp. 47–55, Jun. 2019.

[29] R. Mahmoudi, A. Emrouznejad, S.-N. Shetab-Boushehri, and S. R. Hejazi, "The origins, development and future directions of data envelopment analysis approach in transportation systems," *Socio-Econ. Planning Sci.*, vol. 69, Mar. 2020, Art. no. 100672.

[30] Y. S. Park, S. H. Lim, G. Egilmez, and J. Szmerekovsky, "Environmental efficiency assessment of U.S. Transport sector: A slack-based data envelopment analysis approach," *Transp. Res. D, Transp. Environ.*, vol. 61, pp. 152–164, Jun. 2018.

[31] J. Cui, J. Lang, T. Chen, S. Cheng, and Y. Li, "Emergency monitoring layout method for sudden air pollution accidents based on a dispersion model, fuzzy evaluation, and post-optimality analysis," *Atmos. Environ.*, vol. 222, Feb. 2020, Art. no. 117124.

[32] S. Seker and N. Aydin, "Sustainable public transportation system evaluation: A novel two-stage hybrid method based on IVIF-AHP and CODAS," *Int. J. Fuzzy Syst.*, vol. 22, no. 1, pp. 257–272, Feb. 2020.

[33] F. Ma, J. He, J. Ma, and S. Xia, "Evaluation of urban green transportation planning based on central point triangle whiten weight function and entropy-AHP," *Transp. Res. Proc.*, vol. 25, pp. 3634–3644, Jan. 2017.

[34] A. Blagojevic, S. Veskovic, S. Kasalica, A. Gojic, and A. Allamani, "The application of the fuzzy AHP and DEA for measuring the efficiency of freight transport railway undertakings," *Oper. Res. Eng. Sci., Theory Appl.*, vol. 3, no. 2, pp. 1–23, Aug. 2020.

[35] W. Huang, B. Shuai, Y. Sun, Y. Wang, and E. Antwi, "Using entropy-TOPSIS method to evaluate urban rail transit system operation performance: The China case," *Transp. Res. A, Policy Pract.*, vol. 111, pp. 292–303, May 2018.

[36] C. Yuan, D. Wu, and H. Liu, "Using grey relational analysis to evaluate energy consumption, CO_2 emissions and growth patterns in China's provincial transportation sectors," *Int. J. Environ. Res. Public Health*, vol. 14, no. 12, p. 1536, Dec. 2017.

[37] M. Lu and K. Wevers, "Application of grey relational analysis for evaluating road traffic safety measures: Advanced driver assistance systems against infrastructure redesign," *IET Intell. Transp. Syst.*, vol. 1, no. 1, pp. 3–14, 2007.

[38] M. Hu and N. Bhouri, "Evaluation of resilience indicators for public transportation networks by the grey relational analysis," in *Proc. IEEE 23rd Int. Conf. Intell. Transp. Syst. (ITSC)*, Sep. 2020, pp. 1–6.

[39] L. N. Usenko, "Formation of an integrated accounting and analytical management system for value analysis purposes," *Eur. Res. Stud. J.*, vol. 21, no. 1, pp. 63–71, 2018.

[40] Y. Sun, L. Wang, J. Xu, and G. Lin, "An intelligent coupling 3-grade fuzzy comprehensive evaluation approach with AHP for selection of levitation controller of maglev trains," *IEEE Access*, vol. 8, pp. 99509–99518, 2020.

[41] M. Chen, D. Lu, and L. Zha, "The comprehensive evaluation of China's urbanization and effects on resources and environment," *J. Geographical Sci.*, vol. 20, no. 1, pp. 17–30, Feb. 2010.

[42] J.-F. Chen, H.-N. Hsieh, and Q. H. Do, "Evaluating teaching performance based on fuzzy AHP and comprehensive evaluation approach," *Appl. Soft Comput.*, vol. 28, pp. 100–108, Mar. 2015.

[43] R. Mahmoudi, S. N. Shetab-Boushehri, S. R. Hejazi, and A. Emrouznejad, "Determining the relative importance of sustainability evaluation criteria of urban transportation network," *Sustain. Cities Soc.*, vol. 47, May 2019, Art. no. 101493.

[44] V. L'upták, J. Ližbetin, and L. Bartuška, "A case study of the evaluation of the quality of connections on the railway transport network in the south bohemian region," *Transp. Res. Proc.*, vol. 53, pp. 66–71, Jan. 2021.

[45] W. Niu and X. Wang, "Risk evaluation of railway coal transportation network based on multi level grey evaluation model," in *Proc. IOP Conf., Earth Environ. Sci.*, 2018, vol. 108, no. 4, p. 42108.

[46] T. Watanabe, M. Shibata, and T. Suzuki, "Evaluation of inter-regional transportation network considering multi-mode route alternatives," *Asian Transp. Stud.*, vol. 4, no. 1, pp. 210–227, 2016.

[47] Y. Yang, J. Chen, and Z. Du, "Analysis of the passenger flow transfer capacity of a bus-subway transfer hub in an urban multi-mode transportation network," *Sustainability*, vol. 12, no. 6, p. 2435, Mar. 2020.

[48] M. A. Saif, M. M. Zefreh, and A. Torok, "Public transport accessibility: A literature review," *Periodica Polytechnica Transp. Eng.*, vol. 47, no. 1, pp. 36–43, May 2018.

[49] S. Çolak, A. Lima, and M. C. González, "Understanding congested travel in urban areas," *Nature Commun.*, vol. 7, no. 1, p. 10793, 2016.

[50] X. Kong, Z. Xu, G. Shen, J. Wang, Q. Yang, and B. Zhang, "Urban traffic congestion estimation and prediction based on floating car trajectory data," *Future Generat. Comput. Syst.*, vol. 61, pp. 97–107, Aug. 2016.

[51] Ż. Jacek, "Design and evaluation of transportation systems," in *Proc. Sci. Tech. Conf. Transp. Syst. Pract.* Cham, Switzerland: Springer, 2017, pp. 3–29.

[52] M. C. Branch, *Comprehensive City Planning: Introduction & Explanation*. Evanston, IL, USA: Routledge, 2018.

CHANGJIANG ZHENG received the Ph.D. degree in transportation planning and management from Southeast University, in 2006. He is currently a Professor and a Doctoral Supervisor of the College of Civil and Transportation Engineering, Hohai University. His current research interests include different aspects of transportation planning and management.

YUHANG GU received the bachelor's degree from the Guilin University of Electronic Technology. He is currently pursuing the master's degree with the College of Civil and Transportation Engineering, Hohai University, China. His research interests include the path optimization under connected environment and multimodal transport.

JINXING SHEN received the M.S. degree from Hohai University, in 2009, and the Ph.D. degree in transportation planning and management from Southeast University, in 2015. He is currently an Associate Professor and a Master Supervisor of the College of Civil and Transportation Engineering, Hohai University. His research interest includes the optimization of the multimodal public transportation systems.

MUQING DU received the Ph.D. degree in transportation planning and management from Southeast University, in 2014. He is currently an Associate Professor and a Master Supervisor of the College of Civil and Transportation Engineering, Hohai University. His current research interests include the optimization model and algorithm of traffic networks.

GENGHUA MA received the bachelor's degree from Hohai University, in 2006. She is currently an Experimentalist with the College of Harbour, Coastal and Offshore Engineering, Hohai University. Her current research interests include the harbour waterway design and traffic planning.

KAI SUN received the bachelor's degree from the Guilin University of Electronic Technology. He is currently pursuing the master's degree with the College of Civil and Transportation Engineering, Hohai University, China. His research interest includes the sustainable transport.