Modeling and Analysis of Integrated Transport Comprehensive Carrying Capacity in Urban Agglomerations Considering Carbon Emission

Xuelin Li, Changfeng Zhu, Linna Cheng, and Jie Wang

Abstract-China's rapid urbanization has led to the development of integrated transport networks, which requires the transport sector to pay particular attention to the integrated transport comprehensive carrying capacity (ITCCC). Concurrently, global climate change has focused the world community's attention on greenhouse gas concentrations like CO2. This study establishes an ITCCC measurement model of urban agglomerations (UAs) and measures the comprehensive carrying capacity from four factors: socio-economic, basic resources, transport facilities, and traffic environment. In particular, this paper takes carbon emission as a critical indicator of the traffic environment when considering the impact factors of ITCCC. Based on the data of China's five major UAs, this study estimates carrying capacity levels with the ITCCC model and analyses regional characteristics using the spatial-temporal differentiation method. The results show that the traffic environment significantly impacts the ITCCC. Further low-carbon transport policies and measures are recommended to achieve sustainable development of integrated transport in UAs.

Index Terms—traffic environment; integrated transport; traffic carrying capacity; integrated transport comprehensive carrying capacity; carbon emission

I. INTRODUCTION

In recent years, with the acceleration of urbanization and the continuous improvement of the integrated transport network, the integrated transport comprehensive carrying capacity (ITCCC) has gradually become a determining element for developing urban agglomerations (UAs) in China. Traffic carrying capacity is the key to achieving sustainable urban transport development.

In addition to helping to coordinate the internal workings of the transport system and to allocate resources better, the

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Jie Wang is a PhD candidate at School of Traffic and Transportation, Lanzhou Jiaotong University, Lanzhou 730070, China. (e-mail: 1009696615@qq. com). research of traffic carrying capacity can provide assessments and early warnings for the sustainability of traffic.

As a result, differentiated traffic management strategies will be developed, urban traffic carrying capacity will be increased, and a more scientific theoretical framework for planning, designing, operating, and controlling road traffic systems will be provided. For the assessment and implementation of sustainable development of urban transport in China, it has practical significance, application, and promotion value.

At the same time, the rapid development of comprehensive transportation has increasingly obvious stress on urban resources and the ecological environment. The restriction of environment on the carrying capacity of integrated transport has become an important measure of regional healthy development.

With the prominent manifestation of climate warming and glacial melting, several countries and regions worldwide have established the goal of reaching carbon neutrality around the middle of this century. There is an urgent need for various carbon-emitting industries to seek low-carbon avenues to address the increasingly prominent environmental issues. In building the ITCCC model that accounts for transport carbon emission, carbon emission is employed as a traffic environmental characterization indicator. This is necessary for implementing sustainable development and constructing an ecological civilization. It can also assist urban agglomerations (UAs) in defining the development priorities of comprehensive transport networks and achieving the coordination of transport and the ecological environment.

II. LITERATURE REVIEW

In 1956, Ford and Fulkerson [1] proposed the road network capacity. Subsequently, some scholars such as Fukushima [2], Ardekani and Herman [3] studied the road network capacity using the improved Frank-Wolfe algorithm and the variational analysis method. In 1997, Wong and Yang [4] studied the potential capacity of road networks under signal control, which gradually evolved into studying the road carrying capacity.

The references [5][6][7][8] have enriched the research results on traffic carrying capacity with a large number of studies on road traffic carrying capacity using methods such as the spatiotemporal dissipation method [5] and MFD dynamics [6]. Particularly, Jia [7] and Mirzahossein[8], when the former studied the urban traffic state based on the carrying capacity of road networks, especially considering the travel characteristics of residents and analyzed the

influence of human behavior on the traffic carrying capacity; the latter studied the carrying capacity of highways by adding environmental constraints and analysed some highway sections in Tehran as objects, advancing the study of the integration of traffic carrying capacity and environment. [9] summarised the current state of research on the carrying capacity of urban road traffic at home and abroad, and put forward problems and development suggestions from basic theory, quantitative research methods, and practical applications.

The above literature has laid a solid foundation for the study of traffic carrying capacity and confirmed that traffic carrying capacity is of great value to the control and planning of urban traffic networks. However, the above literature is limited to the study of single transportation modes of road traffic.

With the construction of integrated transport networks, the traffic carrying capacity study object was gradually extended beyond roadways to railways and airplanes.

The references [10][11][12][13][14][15] examined the traffic carrying capacity of railways primarily from three perspectives: railway line carrying capacity [14], railway network carrying capacity [10][11], and railway node carrying capacity [13][15]. In addition, [12] studied railway infrastructure and improved railway transport capacity. Beginning in 1994, scholars represented by Ratcliffe [16] have filled the void in research on the carrying capacity of aviation from several angles [16][17][18]. Dekker [18] particularly incorporated terrain, geopolitical, and environmental variables to examine the carrying capacity of airspace sectors, air routes, and direct flight routes, as well as their combined carrying capacity, to provide solutions to the European airspace carrying capacity issue.

Existing studies have expanded the research width of traffic carrying capacity from different modes of transportation respectively.

With the development of integrated transport, the traffic carrying capacity gradually focused on the study of the integrated transport carrying capacity of the multiple modes of transportation [19][20][21]. [20] incorporated the four modes of transportation of railway, highway, seaport, and airport into the transportation system, assessed the integrated transport carrying capacity using a DEA model considering three subsystems: infrastructure, economic development, and potential demand, which expanded the research on the comprehensive carrying capacity of integrated transport, but lacked the integration with environmental factor.

ITCCC is an organic combination of integrated traffic carrying capacity and comprehensive carrying capacity including social economy, population development, urban evolution, energy space, and ecological environment, to realize the synergy between integrated transport system and the urban comprehensive elements.

When studying the comprehensive carrying capacity of UAs, scholars mainly learn it from economic, demographic, cultural, tourism, and comprehensive perspectives [22][23] [24]. When studying the comprehensive carrying capacity at the transport level, it is also necessary to consider the carrying capacity of transport infrastructure and traffic environment. The literature [25][26][27] explores the supporting capacity of the transport system in terms of the

carrying capacity of transport infrastructure. Among them, [26] studied the impact of the transport system on the regional economy by starting from the carrying capacity of the transport infrastructure, which to a certain extent, achieved the integration of both the transport infrastructure and economic dimensions.

The assessment of the traffic environment carrying capacity can be refined in two ways: traffic noise [28][29] and pollutant emission [30][31][32][33]. [32] constructed a macro quantitative model of traffic carrying capacity based on "motor vehicle on-road", which consists of three modules: road network resources, fuel supply, and atmospheric environment. In recent years, investigations on the emission of pollutants from the traffic environment have focused increasingly on transport carbon emission [34][35] and PM emission [36][37] due to the deployment of low-carbon and green transport.

As seen in Fig. 1, with the passage of time, the research scope of traffic carrying capacity has expanded from single road traffic carrying capacity to the fields of railway, aviation, and integrated transport. The research perspective on traffic carrying capacity has also been gradually enriched.

The established literature has examined ITCCC from many angles at various phases, enriching the meaning of traffic carrying capacity and laying a solid foundation for the research. Due to the complexity of the traffic system, however, the factors considered in the various traffic carrying capacity models still need to be exhaustive, and there are limitations to the actual application scenarios. The deficiencies are mainly evident in the following:

i. Existing traffic carrying capacity studies primarily focus on road traffic or independently analyze other transport modes such as rail and air. More integrated traffic carrying capacity needs to be.

ii. Most research on comprehensive traffic carrying capacity mainly focuses on the two influencing factors of transport infrastructure and socio-economy, ignoring the restrictions of the traffic environment. Specifically, the impact of transport carbon emission on the ITCCC has yet to be considered.

In summary, this paper has three innovations compared to previous studies. Firstly, in analyzing the factors affecting ITCCC, this paper integrates the three factors of socioeconomic, infrastructure resources, and transport facilities, and also considers the transport environment factor with transport carbon emission as the leading indicator, which makes the measurement of ITCCC more objective and accurate. Secondly, in contrast to most prior studies' comprehensive indicator evaluation method, this paper presents an ITCCC measuring model considering transport carbon emission. The ITCCC index for the study area is calculated, and the results are more informative.

Thirdly, this paper employs various techniques, such as trend analysis and comparison of spatial and temporal divergence characteristics, to explore in depth the carrying capacity of socio-economic, basic resources, transport facilities, traffic environment, and the status of their comprehensive ITCCC in China's five major UAs, and to analyze the evolutionary process of ITCCC in the last decade. The analysis results can provide a strategic reference for transport planning decision-makers.



Fig. 1. Literature analysis of traffic carrying capacity based on knowledge tree

III. THE ITCCC: AN OVERVIEW

The integrated transport network is an integrated transportation system including railway, highway, aviation, waterway and urban rail transit. Its development depends on the ITCCC. ITCCC is the scale of passenger and freight transport development that the function and structure of the transportation system can withstand when considering multiple influencing factors under specific spatial and temporal conditions. The complexity of ITCCC is reflected in its integration of multiple modes of transport and the integration of different influencing factors.

Among the factors affecting ITCCC, the level of social economic directly determines the development degree of transportation facilities and the development potential of integrated transport in the region. After the integrated transport develops to a specific scale, it will drive regional economic growth and social progress.

As an objective driving force for the evolution of UAs, basic resources will attract foreign investment and promote the construction of new transportation lines. On the other hand, it can provide resources for the mining, smelting, processing and other industries in the region, form a siphon effect from internal and external interaction, and stimulate the rise of social economy.

The level of transport facilities directly determines the

scale of passenger and freight transportation, thus determining the development level of regional integrated transport network. Transport facilities have a promoting effect on local social economy. At the same time, economic growth will also drive the investment and construction of transportation facilities and form a mutual feedback mechanism.

Existing studies have given less consideration to the impact of the environment on ITCCC, nonetheless, the development of an integrated transport network is dependent on more than socio-economic, basic resources, and transport facilities but is also constrained by the regional ecological environment. The traffic environment is sustaining and crucial in resource development, transportation activities, and socioeconomics.

A good ecological environment can improve the happiness of urban residents, and promote the development of tourism and real estate industry to stimulate local economic growth by strengthening the siphon effect of the city. However, the economic rise at the expense of the environment, excessive exploitation of resources, and excessive investment in transport facilities and equipment will have a negative effect on the ecological environment, so that environmental factors and the other three factors form a synergistic relationship of mutual feedback evolution.

This study abstracts a variety of effect indicators that play a crucial part in ITCCC's internal mechanism from four factors: socio-economic (SE), basic resources (BR), transport facilities (TF), and traffic environment (TE). By integrating these variables, we can express the adaptability and carrying capacity of the integrated transport supply to the UAs' transportation demand. Fig. 2 depicts the major significant factors affecting the ITCCC.



Fig. 2. Factors affecting the ITCCC

The SE carrying capacity is used to measure the socio-economic level of the region where the transportation system is located, reflecting the level of regional economic support for integrated transport within a certain period of time. Its relevant indicators usually include regional resident population, regional per capita GDP, regional government fiscal expenditure ratio, etc.

The carrying capacity of BR is used to characterize the carrying state and satisfaction degree of regional land, land resources, energy and other indicators to the dynamic transportation system.

The TF carrying capacity is used to evaluate the carrying capacity of transportation network, transportation channel or transportation hub, which reflects the level of transportation service and whether the supply capacity of transportation infrastructure meets the transportation demand.

Existing literature mainly focuses on the TE carrying capacity from the perspectives of traffic noise and pollutant emission. It tends to study the comprehensive environment of the entire region, making it difficult to determine the degree of compatibility with the transportation system. Considering that the transportation industry is critical in carbon emission, this article assesses the traffic carbon emission of various modes of transportation when studying the TE carrying capacity. It connects the transportation and environmental systems precisely, resulting in a stronger coupling between the two systems.

When the four factors of SE, BR, TF, and TE affect ITCCC, in addition to the internal indicators of each factor, there is also a competitive relationship between the factors. In the process of competition, the elements and their internal indicators have a synergistic effect to promote the orderly development of integrated transport. When looking at each element separately, its evolution is affected by internal impact indicators; when different elements intersect, there will be competition and cooperation between them. Fig. 3 depicts the interactions between the ITCCC system and the influencing factors.



Fig. 3. The interaction between ITCCC-system and each influencing factor

As seen in Fig. 3, the primary conditions and carrying capacity of each influencing factor determine the potential for the construction and development of the integrated transport network. The story of the integrated transport network will also impact the factors, forming a synergistic evolutionary interaction.

In summary, this paper starts with the three factors of SE, BR, and TF, and the four aspects of TE characterized by traffic carbon emissions. The comprehensive study includes ITCCC of various transportation systems and obtains integrated transport network development suggestions under the influence of the TE factor.

IV. METHODOLOGY AND MEASUREMENT MODEL

A. Analysis of factors affecting ITCCC

A.1. Socio-economic influencing factor (SE)

A higher socio-economic carrying capacity indicates a better-developed regional economy, which can accommodate additional traffic facilities and transport volumes, raising the level of ITCCC. The SE carrying index C_{se} quantifies how

regional economic development affects transportation. Among the SE influencing factor, indicators such as regional resident population, population employed in the transport industry, regional GDP per capita, and proportion of provincial government financial expenditures on transport directly influence the ITCCC.

To incorporate various internal SE indicators, the SE carrying level is measured by the Gini coefficient G_{se} . The Gini coefficient approach is a quantitative tool for describing the degree of equilibrium in economic and social resource distribution, etc. Fig. 4 illustrates the Gini coefficient curve, derived by graphing a Lorenz curve. Typically, the cumulative proportion of a region's population or GDP is plotted along the X-axis, while the cumulative percentage of its resources is plotted along the Y-axis. The Gini coefficient is the ratio of area A surrounded by the Lorenz curve, the absolute equity line, to the triangle's location circumscribed by the X-axis, the complete equity line, and X = 100%[38].



Fig. 4. Gini index graph

For the SE element of ITCCC, considering indicators such as regional population, regional economy, and the number of people employed in the transport sector, a formula for the socio-economic element is established based on the Gini coefficient method as the SE carrying capacity calculation model:

$$C_{se} = I_{se} \cdot G_{se}$$

= $I_{se} \cdot [m - \sum_{se=1}^{3} \sum_{j}^{m} (X_{se} - X_{se-1})(Y_{se} + Y_{se-1})]$ (1)

Where I_{se} is the correction coefficient of the SE factor; G_{se} is the Gini coefficient; X_{se} is the cumulative percentage of the regional population, GDP per capita, and the number of people employed in the transport sector; Y_{se} is the cumulative percentage of regional total financial expenditure on transport; and there are *m* regions, j=1, 2, ..., is the number of areas.

A.2. Basic resources influencing factor (BR)

The potential for ITCCC development will increase with a higher regional BR carrying capacity. The BR carrying index C_{br} measures the capacity of a region's natural and social resources to support the transportation system. Among the BR factor, the land area determines the development space of integrated transport, and the regional energy storage capacity reflects the development momentum of integrated transport. Therefore, the land resource carrying index C_{en} and the energy resource carrying index C_{la} should be considered when calculating the BR factor[31]:

$$C_{br} = I_{br} \cdot (\rho C_{en} + \sigma C_{la}) \tag{2}$$

of which

$$C_{\rm en} = \sum_{j}^{m} \sum_{e} \frac{\phi_{ej} \cdot E_{ej}}{\varphi_{ej}}$$
(3)

$$C_{la} = A \cdot \theta \tag{4}$$

Where I_{br} is the correction factor of the basic resources; ϕ_{ej} is the amount of the eth energy used by the transport sector in area *j* as a percentage of the total energy in that area; E_{ej} is the amount of the eth energy in area *j* each year; ϕ_{ej} is the average energy consumption of the transport sector each year; A is the total area of urban land (km²); θ is the proportion of urban transport land to the metropolitan land area; ρ and are scaling parameters, $\rho + \sigma = 1$, and $\rho = \sigma = 0.5$ in this paper.

A.3. Transport facilities influencing factor (TF)

The level of TF affects the degree of development of integrated transport and the scale of transport, which affects the size of the ITCCC. The C_{TF} is used to measure the degree to which the supply capacity of TF is loaded against transport demand.

The relevant indicators of transport facilities are usually network density, the number of transport hubs, and transport equipment ownership. Transport operations transform these hardware indicators into transport indicators, i.e., the volume of passengers and goods transported.

Considering the five standard modes of transport, C_{TFpi} and C_{TFfi} denote the passenger carrying index and freight carrying index of transport facilities for the *i*th mode of transport respectively (*i*=1, 2, ..., 5 for rail, road, water, air, and urban rail transport respectively):

$$C_{TF_{p}} = I_{TF_{p}} \cdot \sum_{i=1}^{5} C_{TF_{pi}} = I_{TF_{p}} \cdot \sum_{i=1}^{5} (1+h_{i}) \frac{d_{i}}{pv_{i}}$$
(5)

$$C_{TF_{f}} = I_{TF_{f}} \cdot \sum_{i=1}^{4} C_{TF_{f}} = I_{TF_{f}} \cdot \sum_{i=1}^{4} (1+h_{i}) \frac{d_{i}}{f_{v_{i}}}$$
(6)

Where I_{TFp} and I_{TFf} are the modified coefficients for passenger and freight transport; *hi* is the coefficient for high-grade transport facilities ("high-grade" example: h_l is the share of regional high-speed railways in the overall railway); d_i is the mileage of the *i*th mode of transport in operation; pv_i and fv_i are the passenger and freight volumes of the *i*th mode of transport respectively. The passenger volume and freight volume of the *i*th mode of transportation. Due to its transport characteristics, urban rail transport is only included in the TF's passenger carrying capacity calculation.

A.4. Traffic environment influencing factor (TE)

Among the traffic environmental impact factors, the pollutants emitted by various transportation activities are self-cleaning after being treated by environmental systems or pollution control enterprises. Excessive pollutant emissions increase the burden on ecological systems and related enterprises, so the TE factor is critical to the impact of ITCCC.

China's national strategy of "Carbon Peaking and Carbon Neutrality" requires the transport industry to pay great attention to the central carbon emission sector. The TE carrying index C_{EF} of the traffic environmental factor is characterized by the carbon emission factor *EF*. Considering the characteristics of transport carbon emission (TCE), the

smaller the value of TCE, the more friendly it is to the environment, and the higher the TE carrying capacity. The C_{EF} is inversely proportional to the EF:

$$C_{EF} = I_{EF} \cdot \frac{1}{EF} \tag{7}$$

Where is the correction factor of the traffic environment; the integrated transport TCE coefficient EF can be divided into the TCE coefficient EP per unit of passenger turnover; the TCE coefficient EH per unit of freight turnover for each mode of transport.

The TCE coefficient EP of per unit passenger turnover of each mode of transport is defined as per capita carbon emission per kilometer when passengers travel. The unit freight turnover TCE coefficient EH is the carbon emission per ton per kilometer during freight transportation. Both depend on the carbon emission characteristics of the various modes of transport and the load factor of each method. It is calculated as follows:

$$EP = \sum_{j}^{m} \sum_{i}^{5} EP_{ij} = \sum_{j}^{m} \sum_{i}^{5} \frac{EF_{ij}}{pv_{ij}}$$
(8)

$$EH = \sum_{j}^{m} \sum_{i}^{4} EH_{ij} = \sum_{j}^{m} \sum_{i}^{4} \frac{EF_{ij}}{f_{V_{ij}}}$$
(9)

Where *EP* is the TCE coefficient per unit passenger turnover, kgCO₂/(person \cdot km); *EH* is the TCE coefficient per unit freight turnover, kgCO₂/(ton \cdot km); *pv*_{ij} and *fv*_{ij} are the passenger and freight volumes of transport mode *i* in region *j*; *EFi* is the TCE coefficient for transport mode *i* based on transport mileage, kgCO₂/ km.

The calculation of the TCE coefficient for different modes of transport is given below.

(1) TCE coefficient for rail transport

$$EF_{1} = \frac{\sum_{e} E_{e} \cdot Z_{e} \cdot \mathbf{I}_{e} \cdot \frac{44}{12}}{R_{1}}$$
(10)

Where E_e is the *e*th energy source's consumption; Z_e is the conversion factor of the *e*th energy source into standard coal; R_I is the railway operating mileage of the measured section; and 44/12 is the carbon conversion factor.

The types of locomotives used for railway transport in China are internal combustion and electric locomotives used in passenger and freight transport. To facilitate the calculation, energy-to-standard coal conversion relationship for different locomotives is given in reference [39], as shown = in Table I.

I ABLE I
THE RELATIONSHIP BETWEEN ENERGY AND STANDARD COAL
CONVERSIONS FOR DIFFERENT RAILWAY LOCOMOTIVES

	Energy consumption (per ton-km)	Converted to standard coal (per ton-km)
Internal combustion	27.3kg	1.46kg
Electric locomotive	101.9kw·h	0.32kg

(2) TCE coefficient for road transport

$$EF_{2} = \begin{cases} \tau + \frac{\omega}{v}, & \text{Oil-operated cars} \\ \frac{U}{100} + \text{I}_{d}, & \text{Electric cars} \end{cases}$$
(11)

Where τ and ω are the internal combustion motor vehicle calculation parameters; v is the vehicle travel speed, km/h; U is the electricity consumption per 100 km, (kw··h)/100km; Id is the electricity carbon emission factor.

Referring to the parameters in the literature [40], the values of τ , ω and U for different motor vehicle models are shown in Table II.

TABLE II	
PARAMETERS FOR DIFFERENT MOTOR VEHICLE TYPES	
	-

Motor Vehicle Types	τ	ω	U
Small passenger vehicle (petrol)	0.134	3.664	-
Small passenger vehicle (diesel)	0.155	3.814	-
Bus (diesel)	0.575	16.207	-
Large goods vehicle (diesel)	0.508	18.460	-
Medium goods vehicle (diesel)	0.335	9.208	-
Light goods vehicle (diesel)	0.261	6.017	-
Micro cargo vehicle (diesel)	0.162	4.145	-
Electric vehicle	-	-	16
Electric bus	-	-	100

(3) TCE coefficient for water transport

$$EF_{3} = \frac{F_{3} \times I_{c}}{R_{3}}$$
(12)

(4) TCE coefficient for air transport

$$EF_4 = \frac{F_4 \times I_m}{R_4} \tag{13}$$

(5) TCE coefficient for urban rail transport

$$EF_{5} = \frac{F_{5} \times I_{d}}{R_{5}}$$
(14)

where Fi (*i*=3,4,5) is the energy consumption corresponding to the *i*th mode of transport (waterborne diesel consumption, aviation paraffin consumption[41], and rail electricity consumption, respectively) in kg; I_c, I_m and I_d are TCE coefficients for waterborne diesel, aviation paraffin, and electricity, respectively; *Ri* (*i*=3,4,5) is the transport mileage of the *i*th mode of transport on the measured section, km.

Referring to the IPCC inventory guidelines [42], the TCE coefficients for energy sources are shown in Table III.

TABLE III						
I CE COEFFIC	IENTS FOR VARIOU	S TRANSPORT	ENERGY OU	JRCES		
Energy types	Standard coal I _e	Electricity I _d	Diesel Ic	Kerosene Im		
TCE coefficients	1.900	1.246	3.096	3.018		

B. ITCCC measurement model

Let C be the ITCCC of the study area m, C_1 , C_2 , ..., C_k denote the carrying capacity of each impacting element:

$$C = f(C_1, C_2, ..., C_k)$$
 (15)

Where f represents how each influencing factor of the ITCCC affects the ITCCC, considering the complexity of the ITCCC system, the relative geometric resource carrying capacity model is introduced to visualize the impact of f.

$$C = \sqrt[k]{C_1 \times C_2 \times \dots \times C_k}$$
(16)

$$C_i = I_i \times Q_i, i = 1, 2, ..., k$$
 (17)

$$I_i = Q_{p0} / Q_{i0}$$
 (18)

Where I_i is the correction factor for each influence factor; Q_{i0} and Q_i are the resources of the reference area and the study

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area, respectively; Q_{p0} is the total amount of relevant influence factors in the reference area [43]. To eliminate the influence of the relative geometric resource carrying capacity model due to the bias of the resource importance, the model is improved by using the principle of traction effect of superior resources and the binding development of insufficient resources [43].

$$\max C^{1} = w_{l} \sum_{i=1}^{k} C_{i} + w_{2} \sum_{\substack{i,l=1\\i\neq l}}^{k} \sqrt[2]{C_{i}C_{l}} + w_{k} \sqrt[k]{C_{l}C_{2}...C_{k}}$$
(19)
$$\int_{\substack{i,l,g=1\\i\neq l\neq g}}^{k} \sqrt[3]{C_{i}C_{l}C_{k}} + w_{k} \sqrt[k]{C_{l}C_{2}...C_{k}}$$
(19)
$$\int_{\substack{i=1\\i\neq l\neq g}}^{k} w_{i} = 1,$$

$$\alpha \leq |w_{i} - w_{l}| \leq \beta$$

$$\delta < w_{i}, w_{l} < 1$$

$$i,l = 1, 2, ..., k; i \neq l$$

$$\min C^{2} = w_{l} \sum_{i=1}^{k} C_{i} + w_{2} \sum_{\substack{i,l=1\\i\neq l}}^{k} \sqrt[2]{C_{i}C_{l}} + w_{k} \sqrt[k]{C_{l}C_{2}...C_{k}}$$
(20)
$$\int_{\substack{i=1\\i\neq l\neq g}}^{k} w_{i} = 1,$$

$$\alpha \leq |w_{i} - w_{l}| \leq \beta$$

$$\delta < w_{i}, w_{l} < 1$$

$$i,l = 1, 2, ..., k; i \neq l$$

$$C = \sqrt{C^{1}C^{2}}$$
(21)

Close geometrization helps the carrying capacity model with maximum carrying capacity and minimum carrying capacity

is established as models. In models (19) and (20), α and β are the upper and lower limits of the weight differences between the subsystems, respectively; δ is the lower limit of the weights of each subsystem. For the comprehensive carrying capacity problem of integrated traffic, the initial parameters α =0.05, β =0.3, and δ =0.2 are set.

According to the definition of ITCCC, it is divided into the integrated passenger carrying capacity and the integrated freight carrying capacity of transportation, denoted as C_p and C_f . After adding the environmental carrying index of transport characterized by the TCE coefficient, the ITCCC model is modified to obtain the ITCCC model of area j considering ecological pollution.

$$C_{p} = \sum_{j}^{m} \sum_{i}^{5} \lambda_{p_{ij}} \cdot C_{EP_{ij}} \cdot C_{p_{ij}} = \sum_{j}^{m} \sum_{i}^{5} \lambda_{p_{ij}} \cdot \frac{1}{EP_{ij}} \cdot \frac{1}{\sqrt{\max_{ij} (C_{se}^{1}, C_{br}^{1}, C_{TFp}^{1}) \cdot \min_{ij} (C_{se}^{2}, C_{br}^{2}, C_{TFp}^{2})}}$$
(22)

$$C_{f} = \sum_{j}^{m} \sum_{i}^{4} \lambda_{fij} \cdot C_{EHij} \cdot C_{fij} = \sum_{j}^{m} \sum_{i}^{4} \lambda_{fij} \cdot \frac{1}{EH_{ij}} \cdot \sqrt{\max_{ij}(C_{se}^{1}, C_{br}^{1}, C_{TF_{f}}^{1}) \cdot \min_{ij}(C_{se}^{2}, C_{br}^{2}, C_{TF_{f}}^{2})}$$
(23)

where C_p and C_f are the combined passenger and freight carrying capacity of integrated transport in region *j*, respectively; *C* is the total carrying capacity of the area; λ_{pij} is the transport mode weighting factor, the value of which is equal to the ratio of the passenger volume of the *i*th transport mode to the total passenger volume in region *j*; λ_{fij} is the same; EP_{ij} and EH_{ij} are the TCE coefficients per unit of passenger and freight turnover of the *i*th transport mode in region *j*, respectively.

Based on the TOC constraint theory, the integrated transport comprehensive carrying capacity C can be expressed as the following equation:

$$C = \min\{C_P, C_f\} \tag{24}$$



Fig. 5. China's five national-level UAs and 30 typical cities

V.EMPIRICAL ANALYSIS

The five national UAs of Beijing-Tianjin-Hebei, Yangtze River Delta, Pearl River Delta, Middle reaches of Yangtze River and Chengdu-Chongqing, and 30 typical cities in these agglomerations, were selected as the target of the study. These cities have developed economies, large populations, and high pressure on resources and the environment, representing UAs' transport carrying capacity. The ITCCC indexes of the five major UAs without considering carbon emission and considering carbon emission were measured and analyzed. The study area is shown in Fig. 5.

The relevant primary data were obtained from the 2010-2021 China Urban Statistical Yearbook, the 2010-2021 statistical yearbooks of various provinces and municipalities, the China Port Statistical Yearbook, the Environmental Quality Bulletin, and the China Environmental Statistical Yearbook. After obtaining the relevant initial data, the historical data method was used to process the missing data to compensate for the errors and used MATLAB programming to obtain the calculation results of ITCCC.

A. Analysis of factors affecting ITCCC

The carrying capacity of the five major UAs from 2010-2021 is analyzed from the perspective of four factors affecting the ITCCC: SE, BR, TF, and TE.

Table IV to Table VIII show the SE, BR, TF, TE carrying capacity indexes and ITCCC indexes without considering carbon emission and considering carbon emission of Beijing-Tianjin-Hebei UA, Yangtze River Delta UA, Pearl River Delta UA, Middle reaches of Yangtze River UA, and Chengdu-Chongqing UA respectively.

TABLE IV FOUR SUBSYSTEM INDEXES AND COMPREHENSIVE INDEXES OF BEIJING-TIANJIN-HEBEI UA

	SE	BR	TF	TE	ITCCC	ITCCC (TE)
2010	0.438	0.457	0.500	0.569	0.455	0.264
2011	0.433	0.492	0.501	0.553	0.484	0.280
2012	0.425	0.526	0.527	0.571	0.499	0.288
2013	0.400	0.539	0.559	0.583	0.512	0.297
2014	0.449	0.564	0.578	0.590	0.515	0.298
2015	0.383	0.584	0.614	0.588	0.541	0.312
2016	0.456	0.631	0.623	0.973	0.542	0.531
2017	0.368	0.652	0.654	0.999	0.582	0.568
2018	0.452	0.684	0.682	1.036	0.564	0.553
2019	0.469	0.699	0.699	1.035	0.610	0.596
2020	0.406	0.719	0.719	1.113	0.609	0.685
2021	0.458	0.736	0.733	1.043	0.625	0.659

TABLE V Four Subsystem Indexes and Comprehensive Indexes of Yangtze River Del ta UA

		TANUIZ	E KIVEK I	JELIA UF		
	SE	BR	TF	TE	ITCCC	ITCCC (TE)
2010	0.419	0.434	0.543	0.771	0.451	0.371
2011	0.400	0.466	0.565	0.790	0.482	0.396
2012	0.420	0.504	0.588	0.799	0.501	0.414
2013	0.420	0.534	0.613	0.820	0.523	0.431
2014	0.409	0.568	0.642	0.835	0.537	0.444
2015	0.455	0.601	0.675	0.839	0.566	0.467
2016	0.478	0.635	0.694	1.218	0.583	0.716
2017	0.436	0.665	0.717	1.241	0.572	0.703
2018	0.402	0.677	0.730	1.261	0.603	0.742
2019	0.397	0.697	0.751	1.293	0.617	0.759
2020	0.456	0.745	0.786	1.335	0.623	0.832
2021	0.441	0.759	0.796	1.243	0.641	0.793

TABLE VI FOUR SUBSYSTEM INDEXES AND COMPREHENSIVE INDEXES OF DEADL DIVED DELTA UA

		I EAKL	KIVEK DI	ELIA UA		
	SE	BR	TF	TE	ITCCC	ITCCC (TE)
2010	0.415	0.515	0.519	0.722	0.471	0.357
2011	0.355	0.531	0.539	0.733	0.482	0.366
2012	0.467	0.558	0.560	0.745	0.516	0.391
2013	0.441	0.586	0.582	0.750	0.525	0.398
2014	0.436	0.605	0.607	0.758	0.534	0.405
2015	0.434	0.634	0.634	0.758	0.569	0.432
2016	0.433	0.666	0.673	1.152	0.598	0.694
2017	0.434	0.692	0.704	1.169	0.611	0.709
2018	0.408	0.717	0.743	1.189	0.597	0.692
2019	0.446	0.721	0.759	1.207	0.644	0.746
2020	0.425	0.731	0.791	1.258	0.637	0.802
2021	0.476	0.774	0.815	1.208	0.665	0.804

TABLE VII Four Subsystem Indexes and Comprehensive Indexes of Middle reaches of Yangtze River UA

	SE	BR	TF	TE	ITCCC	ITCCC (TE)
2010	0.508	0.313	0.391	0.685	0.373	0.269
2011	0.433	0.341	0.421	0.690	0.404	0.292
2012	0.410	0.351	0.442	0.700	0.386	0.279
2013	0.496	0.406	0.476	0.708	0.429	0.309
2014	0.367	0.436	0.497	0.717	0.440	0.317
2015	0.412	0.462	0.533	0.721	0.457	0.330
2016	0.422	0.479	0.553	1.119	0.460	0.517
2017	0.457	0.498	0.571	1.136	0.507	0.569
2018	0.429	0.535	0.591	1.157	0.486	0.545
2019	0.451	0.541	0.611	1.186	0.528	0.591
2020	0.476	0.583	0.632	1.222	0.553	0.676
2021	0.483	0.595	0.653	1,171	0.570	0.668

TABLE VIII FOUR SUBSYSTEM INDEXES AND COMPREHENSIVE INDEXES OF CHENGDU-CHONGQING UA

				-		
	SE	BR	TF	TE	ITCCC	ITCCC (TE)
2010	0.423	0.323	0.406	0.743	0.366	0.288
2011	0.410	0.355	0.424	0.746	0.401	0.316
2012	0.370	0.385	0.464	0.762	0.423	0.333
2013	0.459	0.389	0.481	0.767	0.431	0.339
2014	0.437	0.423	0.509	0.778	0.459	0.361
2015	0.415	0.452	0.540	0.783	0.482	0.379
2016	0.460	0.462	0.566	1.181	0.480	0.570
2017	0.453	0.493	0.589	1.203	0.499	0.592
2018	0.454	0.526	0.617	1.218	0.530	0.629
2019	0.406	0.554	0.630	1.252	0.540	0.641
2020	0.435	0.590	0.658	1.283	0.538	0.692
2021	0.426	0.616	0.677	1.225	0.560	0.688

A.1 Traffic carrying condition based on SE factor

According to the formulas and related data to calculate the bearing index of the five major UAs from 2010 to 2021, the carrying capacity index based on the socio-economic (SE) factor is obtained, as shown in Fig. 6.

As seen from Fig. 6, although the SE carrying capacity indexes for the five UAs fluctuate and do not have a uniform trend, the overall average shows an upward trend year on year. The variability of the index of different UAs is because each UA's population, economic and financial data are quite different. The index for the Beijing-Tianjin-Hebei and the Middle reaches of the Yangtze River UAs are more volatile. In contrast, the Pearl River Delta UA index fluctuates more moderately. In terms of the curve changes from 2020 to 2021, the SE carrying capacity indices of the three UAs of Beijing-Tianjin-Hebei, the Pearl River Delta, and the Middle reaches of the Yangtze River are on an upward trend, while the SE indices of Chengdu-Chongqing and Yangtze River Delta are on a downward trend.



Fig. 6. Integrated transport carrying capacity index curve based on socio-economic factor

This is related to the economic and social development of each city group in these two years and the degree of influence of COVID-19. A stable SE carrying index favors the traffic carrying capacity, and regions should actively adjust their policies to promote steady economic development.

A.2 Traffic carrying conditions based on BR and TF factors

The integrated transport carrying indices based on the BR and TF factors are shown in Fig. 7 and Fig. 8, respectively.



Fig. 7. Integrated transport carrying capacity index curve based on basic resource factor

As seen from Fig. 7 and Fig. 8, these two indices of the five significant UAs have shown a steady upward trend year by year since the 12th year. Among the five major UAs, the BR Index and TF Index curves for Beijing-Tianjin-Hebei, Yangtze River Delta, and Pearl River Delta lie above the mean curve. In contrast, the curves of the indices for the Middle reaches of the Yangtze River and the Chengdu-Chongqing lie below the mean. They are focusing on developing basic resources and transport facilities in UAs. Beijing, the capital of China, is located in the Beijing-Tianjin-Hebei region. Shanghai, the economic center, is located in the Yangtze River Delta region was the first region in China to implement reform and opening-up policies. These three UAs, which

developed early and are rich in resources, have significant advantages. They are also the most densely developed regarding China's high-speed rail network and airport routes.



Fig. 8. Integrated transport carrying capacity index curve based on transport facility factor

Although the Middle reaches of the Yangtze River and the Chengdu-Chongqing UAs are somewhat different from the above three UAs, they also have more significant potential for developing basic resources and constructing transport facilities. Both should vigorously promote the construction of integrated transportation networks, drive the rise of BR and TF traffic carrying indices, thereby strengthening the ITCCC in the region and promoting local development.

A.3 Traffic carrying condition based on TE factor

Fig. 9 depicts the ITCCC indexes curve based on the TE factor. The UAs demonstrate a substantial superiority and inferiority ranking concerning transport carbon emission.

From an overall perspective, the TE traffic carrying index curves for the five major UAs fluctuate consistently, with all showing a significant jump in 2016 and a slight increase in 2020. China proposed in 2016 to adjust its transport structure by reducing the proportion of freight transported by road and adopting the more environmentally friendly and cleaner rail or water transport to take up this portion of freight traffic as pressure on environmental protection increases due to CO₂ and other pollutant emission.



Fig. 9. Integrated transport carrying capacity index curve based on traffic environment factor

The reduction in carbon emission from transportation has directly affected the transport environmental carrying index, causing it to increase substantially. China was severely devastated by the COVID-19 that ravaged the planet in 2020. Road closures and route shutdowns were implemented to varying degrees in various places, resulting in decreased logistics and transport and, consequently, transport carbon emissions.

From the perspective of each UA, the TE carrying index of the Yangtze River Delta UA has steadily ranked first for 12 years, followed by the Chengdu-Chongqing UA. The Beijing-Tianjin-Hebei UA has the fifth-highest TE index, and there is a particular gap between the TE index and the other four UAs. The Yangtze River Delta UA is rich in vegetation and water resources and has a strong capacity for ecological self-care. At the same time, the Yangtze River Delta UA has a well-developed inland water transport system and a "one-hour high-speed railway network [45]", and the railway and water transport, which produce less traffic carbon emission, take up a considerable part of the transport volume, making the traffic environment carrying index higher.

The higher TE carrying level of the Chengdu-Chongqing UA is partly because the Chengdu-Chongqing region also has a better natural ecological environment; on the other hand, the traffic volume in the Chengdu-Chongqing region is not very large, which reduces the pressure on the traffic environment. The Beijing-Tianjin-Hebei UA borders Inner Mongolia to the west. Many heavy industries and enterprises with high pollution emission in the region suffered from dust and hazy weather before 2016. This situation only improved after the environmental reforms in 2016.

The carrying level of the transport environment is crucial, and each city cluster should develop a green, low-carbon, and environmentally friendly integrated transport network, taking into account its realities.

B. Analysis of ITCCC

To further reveal the influence of transport environmental impact factors on the ITCCC, the ITCCC indices of the five major UAs without and with transport carbon emission were calculated separately. The trends of ITCCC curves without considering and considering transport environmental impact factors are shown in Fig. 10 and Fig. 11, respectively.

Fig. 10 shows the ITCCC without considering transport carbon emission, encapsulates the three influencing factors of SE, BE, and TF. Its ITCCC curve, after being influenced by the SE factor to produce fluctuations, shows similar characteristics to the carrying capacity curves of the BR and TF factors.

The ITCCC indices of the three UAs of Beijing-Tianjin-Hebei, Yangtze River Delta, and Pearl River Delta are higher than the average. The index of the Pearl River Delta UA is the highest among the five UAs, showing the significant development advantage of the Pearl River Delta region as the first reform and opening-up region in China.

In contrast, the indexes of the Yangtze River Delta and the Pearl River Delta UAs are similar and rank second. The index for the Middle reaches of the Yangtze River and Chengdu-Chongqing UAs are below the mean, with the carrying index for the Middle reaches of the Yangtze River UA being slightly lower than the Chengdu-Chongqing UA overall.



Fig. 10. ITCCC without considering traffic environmental factor



Fig. 11. ITCCC considering traffic environmental factor

Fig. 11 shows that the shape of the ITCCC curve for the integrated traffic carrying capacity considering the traffic environment shows a significant difference from the body of the ITCCC curve without considering the environment. This is mainly due to the correction effect of the environment subsystem on the value taken for the carrying capacity. It can be seen that after adding the TE influence factor, the index of the Yangtze River Delta UA, and the ITCCC(TE) curve of the Chengdu-Chongqing UA rises to third place around the mean. The Beijing-Tianjin-Hebei UA, which was above the average, has fallen to fifth place alongside the Middle reaches of the Yangtze River UA due to its relatively low ecological and transport environment level.

In order to further reveal the relationship between the ITCCC index considering the environment and the ITCCC index without considering the environment, the ITCCC index and the ITCCC (TE) index of the five major UAs in China are analyzed, as shown in Fig. 12. As shown in Fig. 12, ITCCC without and with traffic environment taken into account show a long-term upward trend between 2010 and 2021. This indicates that China's integrated transport carrying level is becoming more sustainable.

In Figure 12, the difference between the two curves shows the degree of influence of TE factors on ITCCC and the corresponding time nodes. The upward trend of ITCCC curve without considering TE is relatively stable, and the average change rate is about 4.47 % per year. Although the ITCCC curve considering TE is also increasing year by year, there







Fig. 12. ITCCC considering TE factor and without considering TE factor based on China's five UAs and the overall scale

The first stage is 2010-2015. The average growth rate of the ITCCC curve considering TE is about 4.2 % per year, which is lower than the ITCCC growth rate without considering TE in the same period. It shows that the traffic environment and carbon emissions at this stage inhibit the improvement of ITCCC. Specifically, 2010-2015 is a period of rapid economic development in China. A large number of freight operations in the transportation industry are undertaken by long-distance trucks, resulting in serious carbon emissions and environmental burdens.

2016-2019 is the second stage. The growth level of the ITCCC curve considering TE tends to be stable, with an average growth rate of about 2.6 % per year. The ITCCC (TE) curve growth rate of this stage reached 26.4 %, which was much higher than the previous curve growth rate. It shows that carbon emissions and traffic environment have been raised to a better level. It is because since 2016, China enacted more than a dozen environmental policies and regulations. Transport-related policies such as the "Winning the Blue-sky War" plan [46] and the "road-to-rail" reform not only reduced the amount of freight transported by road but also reduced congestion in cities.

2020 is the third stage so far. Affected by the COVID-19 epidemic in 2020, the trend of ITCCC(TE) curve has declined. On the one hand, COVID-19 had affected China's transportation and logistics, and transport carbon emissions have been further reduced; on the other hand, the closure policy implemented by many cities has reduced the travel and activities of urban residents, and the ecological environment has been self-purification and repaired. After the end of the COVID-19, social activities and residents' lives returned to normal levels, traffic carbon emission increased, and environmental levels declined.

Through the analysis of the ITCCC of the five major UAs, it can be concluded that environmental and traffic carbon emission have a significant impact on the integrated transport comprehensive carrying capacity in a region. Each region should pay attention to environmental constraints while developing its economy and promoting the construction of integrated transport facilities.

C. Comparison of traffic carrying capacity between different transportation modes

To identify the critical directions for the development of integrated transport in the five UAs, further research should be conducted to analyze the carrying capacity of each transport mode in the UAs.

The integrated transport network comprises four transport modes: rail, road, water, and air, each of which shares socio-economic and infrastructural resources. To investigate the carrying level of each transport mode, the proportion and variation of each transport mode are studied from two perspectives: TF and TE carrying index. The TF indices of the four transportation modes in different UAs are shown in Fig. 13.



As seen in Fig. 13, among the five major UAs, railway has the highest TF index, followed by road. The railway indexes of the Yangtze River Delta and Pearl River Delta UAs are higher than that of other UAs, indicating that the railway networks of these UAs are relatively dense. The highway indexes of the Beijing-Tianjin-Hebei and the Middle Yangtze River UAs are higher than that of other UAs, indicating that the road transportation of these two UAs is relatively developed. The water transportation indexes of the Yangtze River Delta and Pearl River Delta UAs are higher than that of the other three UAs. The aviation index differences among the five UAs are relatively small.

The TCE of four transportation modes in different UAs is shown in Fig. 14. It is clear from the figure that road transport carbon emission is much greater than the other three transportation modes in each UA, with an average share of around 80%, and air transport carbon emission is the lowest, with an average percentage of less than 5%.



The UAs should combine their regional advantages and vigorously develop railway and water transport, transferring the transport volume to railway and water transport modes to reduce road transport's carbon emission. At the same time, each UA should vigorously develop air transport to share the transport pressure of water and land transport.

D.Analysis of spatiotemporal divergence

Carrying	× .	~	2010	2016	2021
Capacity	Level	Graded		Cities	
ITCCC	Uiahan	0.665	None.	Beijing, Shanghai.	Bejing, Chengdu, Nanjing, Shanghai,
	righei				Wuhan, Shenzhen, etc., 8 cities in all.
	High	0.565	Beijing, Shanghai.	Guangzhou, Chengdu, Shenzhen,	Wuxi, Dongguan, Chongqing,
	mgn			Hangzhou, etc., 8 cities in all.	Tangshan, etc., 13 cities in all.
	Medium	0.460	Tianjin, Hangzhou, etc., 7 cities in all.	Tianjin, Foshan, Ningbo, Zigong,	Leshan, Suining, Huanggang,
				Shijiazhuang, etc., 13 cities in all.	Handan, etc., 9 cities in all.
	Low	0.390	Tangshan, Leshan, Chongqing,	Mianyang, Leshan, Zhuzhou,	None.
	2011		Chengdu, Zhuhai, etc., 9 cities in all.	Huangshi, etc., 7 cities in all.	
	Lower	0.310	Handan, Jiaxing, Zhuzhou,	None.	None.
			Dongguan, etc., 12 cities in all.		
ITCCC	Higher	0.780	None.	Hangzhou. Shenzhen.	Bejing, Nanjing, Shanghai, Chengdu,
(TE)	ing.iei				Zhuhai, Suzhou, etc., 10 cities in all.
	High	0.690	None.	Beijing, Shanghai, Chengdu, Zhuhai,	Tianjin, Chongqing, Jiaxing,
	8			Guangzhou, etc., 8 cities in all.	Changsha, etc., 8 cities in all.
	Medium	0.550	None.	Tianjin, Chongqing, Wuhan, Jiaxing,	Shijiazhuang, Jiujiang, Dongguan,
		0.050		Zigong, Foshan, etc., 9 cities in all.	Zhuzhou, Leshan, etc., 9 cities in all.
	Low	0.370	Chengdu, Guangzhou, Nanjing,	Tangshan, Handan, Nanchang,	Huanggang, Handan, Tangshan.
		0.100	Hangzhou, Wuxi, etc., / cities in all.	Zhuzhou, etc., 11 cities in all.	N.
	Lower	0.190	Lianjin, Chongqing, Shijiazhuang,	None.	None.
	-		Wuhan, Foshan, etc., 23 cities in all.		

TABLE IX	
THE FIVE-GRADIENT STRUCTURE OF ITCCC AND ITCCC	(TE) OF 30 CITIES IN FIVE MAJOR UAS



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In order to analyze the spatial and temporal differentiation characteristics of ITCCC and ITCCC(TE) of the five UAs, a five-gradient structure (Lower, Low, Medium, High, Higher) was established.

The results of the visual maps of the temporal evolution and spatial divergence of the ITCCC for 30 cities in the five major UAs in 2010, 2016, and 2021 can be derived from Table IX.

The evolution of the temporal and spatial divergence of ITCCC and ITCCC(TE) for the five major UAs is shown in Fig. 15. Regarding the time dimension, the ITCCC levels in most of the five UAs have steadily improved, with each time point allowing for a gradient of improvement. Among all cities, the ITCCC level of provincial capitals and municipalities is generally higher than that of other ordinary cities in the same period. Compared to 2010, the proportion of high-level ITCCC cities will increase significantly in 2021, mainly in the Yangtze River Delta and Pearl River Delta UAs.

Typically, cities with low ITCCC values are found in the western and central areas. Cities with high ITCCC levels show a multi-stage downward trend from east to west. The spatial and temporal divergence evolution of the SE, BR, TF, and TE influencing factors of the five major UAs is shown in Fig. 16.

Comparing the results of the three-year carrying capacity measurement in the visualization map, it can be seen that the least significant spatial and temporal change among the four impact factors is SE, and the most significant change is the TE factor; the changes of the BR and TF impact factors are more stable and evolve gradually as time advances. Focusing on the TE influencing factor, the Beijing-Tianjin-Hebei UA's traffic environment level is the last among the five UAs.

VI. CONCLUSIONS AND DISCUSSIONS

This paper aims to explore the comprehensive carrying capacity of integrated transport based on UAs, to analyze in depth the factors affecting the ITCCC, and to reveal the intrinsic mechanism of the ITCCC from the perspective of the evolution of competition and cooperation among the influencing factors, to propose a model for measuring the ITCCC, to measure the size of the ITCCC in China's five major UAs over 12 years, and to analyze the bearing results to provide suggestions for the development of integrated transport.

The main conclusions of this study are:

- (1) ITCCC is constrained by socio-economic, basic resources, transport facilities, and traffic environment impact factors. Between 2010 and 2021, the influence of socio-economic factors on ITCCC fluctuated little, while the effect of basic resources and transport facilities factors on ITCCC increased yearly.
- (2) The basic resources, transport facilities, traffic environment, and carrying index are rising from the inland areas of western China to the eastern coastal regions, consistent with economic growth.
- (3) Traffic environment is the most influential factor for ITCCC. The contribution of TE to the ITCCC averaged 33.45% from 2010-2016 and 40.16% from 2016-2021. Among them, the TE carrying index of the Yangtz River Delta UA was the highest during the study period,

followed by the Chengdu-Chongqing UA. The TE index of the Beijing-Tianjin-Hebei UA ranked last. The traffic environment of the Beijing-Tianjin-Hebei region should be improved through transport structure adjustment and green and low-carbon travel.

- (4) The spatial variability in carrying levels over time is indicative of the relatively low level of regional integration in China. Overall the carrying capacity of each impact factor in the Yangtze River Delta and Pearl River Delta UAs is significantly higher than the average level of the five major UAs.
- (5) According to the analysis' findings, the most carbon emissions are produced by the road system, so in order to develop integrated transport in a sustainable and low-carbon manner, road traffic should be diverted to the railroad and water systems, while also taking into account the actual situation of the UAs.

According to the above analysis, the following suggestions are made for the integrated transport in UAs:

- (1) The rise of the IFCCC depends on the efficient coordination of all of its subsystems; on the other hand, any deterioration in a subsystem's performance would result in the failure of the IFCCC as a whole. The state characteristics and influencing factors of each subsystem's carrying capacity should be taken into consideration, along with the carrying capacity of the subsystem that is most unevenly developed, in order to optimize the IFCCC structure.
- (2) Policymakers should pay more attention to spatial differences to achieve adequate support for the regional integrated transport structure by the measured ITCCC values. A top-level design should be made for the coordinated development of ITCCC based on the carrying capacity status of each city. Cities with greater IFCCC should act as growth poles and intensify the radiation effect on nearby cities, such as provincial capitals and municipalities directly under the central government in the five major UAs.
- (3) According to the ITCCC analysis by mode of transport, road transport remains the most polluting transport mode. Low carbon and energy-saving means of transportation should be promoted.
- (4) In the near to medium term, we will improve the energy conversion efficiency of traditional fuel vehicles while promoting new energy vehicles; in the medium to long term, we will popularize the use of new energy vehicles, improve urban public transport systems and reduce the pressure of road saturation. In addition, we need to accelerate scientific and technological research to promote the entry into the use of energy-efficient tools such as electric aircraft, for example.

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