Construction and Evaluation of Urban Sponge Road Traffic System Structure

Chengyuan Mao*, Shengde Yang, Qin Wang, Wenjiao Xu, Peiran Li and Yongliang Zhang

Road and Traffic Engineering Institute, Zhejiang Normal University
Email: maocy@zjnu.cn, yangsd@zjnu.edu.cn, 18816238356@163.com, 985481207@qq.com, 947934423@qq.com
*Corresponding author email: maocy@zjnu.cn

Abstract. The imbalance of traffic resources is one of the important reasons that restrict the healthy development of the urban traffic system. Based on the concept of “sponge city”, this paper puts forward a kind of road traffic system, which can explore the flexible space of transportation infrastructure. The Fuzzy Analytic Hierarchy Process is established to comprehensively evaluate the system performance, deeply explore the flexible space of urban transportation facilities, and improve the performance of the urban transportation system. The sponge-type road traffic system evaluation model proposed in this paper can provide a reference for other regions to tap the flexible space of regional traffic infrastructure resources.

1. Introduction

In recent years, with the rapid development of economic society and urbanization, the road traffic system is constantly improving and developing. However, affected by the disturbances, such as the number of motor vehicles, the transportation infrastructure resources and et al, the urban road traffic system has been strongly impacted, such as the imbalance of traffic supply and demand [1], and the uneven distribution of traffic resources [2], and et al. As a result, many cities have experienced traffic congestion of varying degrees [3], traffic pollution [4], traffic violations [5], and traffic accidents[6], which have seriously reduced the level of traffic services[7], and strongly affects the strategic implementation of transportation planning and new urbanization construction.

The road traffic problem is the reflection of the contradictions of the three elements of human, vehicle, and road in the urban space-time domain [8]. To address the complicated contradiction problem, there is need to evaluate the road traffic system and formulate corresponding strategies. To date, scholars have conducted extensive researches regarding the evaluation methods of road traffic systems. It is considered that the road traffic system is a complex interrelation and self-adaptive system[9], on the basis of introducing the feedback mechanism[10], it is necessary to adopt bottom-up thinking[11] and complex system theory[12] to analyze system-related issues, a road transportation system evaluation model is established with the consideration of transportation technology[13], economy[14], environment[15], and other factors. Besides, some scholars have evaluated the adaptability of the road traffic system from the aspects of urbanization and system synergy [16], economic construction and network coordination [17], system structure performance, and operation quality [18].

Traffic infrastructure resources are an important foundation to the road transportation system, rational construction and optimization of traffic infrastructure resources can promote the maximum use of traffic flexible resources. However, few studies have addressed the flexible space of...
transportation infrastructure resources. In light of this, this article combines qualitative and quantitative methods to build and estimate the sponge-type road traffic system structure based on road infrastructure resources.

2. Construction of Index System of Urban Sponge Road Traffic System

2.1 The Concept of Urban Sponge Road Traffic System

Urban sponge roads refer to the urban road traffic system like a sponge, which has the functions of "absorption" and "exhaustion". Under the premise of not affecting road traffic safety and functions, urban sponge roads can realize the coordination of "time, space, and flow", and achieve the purpose of reducing delays, balancing flow distribution, alleviating traffic congestion.

2.2 Construction of Evaluation Index System

The index of the sponge road traffic system can reflect the elastic space performance. Based on the analysis of the existing literature, the paper puts forward the evaluation indexes, and analyzes the functions and internal structure of the sponge road traffic system from the aspects of its adaptability, technical performance, and operational performance. The framework of the evaluation index system is shown in Figure 1.

2.2.1 Adaptability performance

The adaptability assessment mainly analyses the adaptability of the road traffic system to urban development. Relevant studies have shown [19-20] that there is a close interaction between land use and urban traffic. Therefore, the adaptability assessment can reflect the balance between the land development attributes and traffic infrastructure.

1) The comprehensive density of road network

The comprehensive density of the road network reveals the accessibility of the regional road network and reflects the road network structure. The calculation formula as follows.

\[ \rho = L \cdot (A \cdot P \cdot E_{GDP})^{-1/3} \] (1)

Where \( \rho \) is the comprehensive density of road network, \( \text{km} \cdot (100\text{km}^2 \cdot \text{million people} \cdot \text{billion RMB})^{1/3} \); \( L \) is the total mileage of road network, \( \text{km} \); \( A \) is the area, \( 100\text{km}^2 \); \( P \) is the population, \( \text{million person} \); \( E_{GDP} \) is the GDP, \( \text{billion RMB} \).

2) The road area per capita [21]

It is the ratio of urban road length to the built-up area. Developed countries generally reach 20%-25%, and many cities in China is about 10%-15%. It can measure the degree of development of urban road infrastructure.
(3) Road network coverage rate
It directly affects the traffic quality of the road network and the economic benefits of transportation. Taking regional trunk and secondary trunk roads as the research object of the regional road network, the calculation formula refers to ref.21.

(4) Balance of road network layout
It indicates the rationality of regional spatial layout. It was defined as the percentage of the reasonable zone in the planned area. the calculation formula refers to ref.22.

2.2.2 Technical performance
The technical performance evaluation mainly analyses the road performance of the sponge-type road traffic system through road static index.

(1) Road network-grade level index
It analyses the longitudinal change of road network-grade level and analyses the traffic operation status of the road network.

\[ J = (\sum_{i=1}^{n} J_i \cdot L_i) \cdot L_{alt}^{-1/2} \]  \hspace{1cm} (2)

Where \( J_{rng} \) is the Road network-grade level index; \( J_i \) is the converted factor of the technical grade of road section \( i \), \( J_i \) = \{Expressway, Trunk Road, Secondary Trunk Road, Branch Road\}; \( L_i \) is the total mileage of road section \( i \), km.

(2) Road network connectivity index
The road network connectivity index indicates the maturity of a road network. The value is the higher, it indicates that the less the broken road is, and the higher the ring forming rate is. the calculation formula refer to ref.23.

(3) Accessibility index
It reflects the developed degree of the trunk road network and the distribution of the whole trunk road network. The higher the value is, it shows the form of the traffic is more reasonable and convenient. the calculation formula refers to ref.24.

(4) Non-linear index
The minimum value of the non-linear coefficient is 1. The smaller the non-linear Coefficient is, the more convenient the traffic between two points is. the maximum nonlinear coefficient of the road network is smaller, it indicates that the whole road network is reasonable. the calculation formula refers to ref.24.

(5) Road network-level gradation
The road network level gradation is quantitatively characterized as the proportional relationship between the length and area of each level of the city’s roads, it reflects the comprehensive effect of the urban road structure and functional structure collocation. the calculation formula refers to ref.22.

2.2.3 Operational performance
The operation performance mainly analyses the conformity between the sponge-type road traffic system and traffic demand. The indexes as follows:

(1) Road network jam index
The purpose of the congestion index is to find the "bottleneck" sections of the existing road network. the calculation formula refers to ref.25.

(2) The average speed of the road network
The average speed of road network comprehensively reflects the road condition and vehicle driving condition under the traffic volume of existing road network, which reflects the system performance and traffic quality of road network, the calculation formula refer to ref.26.

(3) Operational efficiency index [23]
The operational efficiency index reflects the degree that the load rate of road network deviates from the average load rate. Obviously, the smaller the value is, the better the load uniformity of the network is.

(4) Operational efficiency index
The operational efficiency of the road network reveals the network’s ability to transport people or goods per unit time. The larger the operational efficiency index is, the better the performance of the system is and the stronger the traffic adaptability is. The calculation formula refer to ref.25.

3. The Model of the Fuzzy Analytic Hierarchy Process

The index of urban sponge road traffic system structure covers many aspects, and each aspect has different emphasis on the sponge road traffic system. Single evaluation methods cannot evaluate the stability and robustness of the sponge road traffic system, such as AHP, The method of fuzzy evaluation, DEA, Grey Comprehensive Evaluation. Thus, it is necessary that the system comprehensive evaluation method is established to integrate the evaluation effect of multiple indexes.

At present, extensively comprehensive methods are proposed. However, the urban sponge traffic system is restricted by many factors, it is difficult to apply an accurate numerical value to measure the stability and robustness. Compared with other comprehensive methods, The Fuzzy Hierarchy analytic method has advantages, such as scientific and practicality, considering many factors, etc. Therefore, the AHP is selected to evaluate the urban sponge road traffic.

3.1 The Determination of the Evaluation Factors and Evaluation Grade

Based on the evaluation index system of sponge road traffic system, the evaluation factor set (index set) is established: \( U = \{u_1, u_2, \ldots, u_{13}\} \), the evaluation level \( V = \{v_1, v_2, v_3, v_4, v_5\} = \{\text{Excellent, good, medium, fair, poor}\} \).

3.2 The Calculation of Index Weight

Generally, the importance of each factor is unequal. To describe the differences, there is a need to calculate the weight of the evaluation index. The analytic hierarchy process integrates the qualitative and quantitative analysis, it is not affected by unfavorable factors, such as goals, criteria, factors, levels, etc. Consequently, The AHP was applied to determine the weight.

3.3 Single-factor Fuzzy Evaluation

The fuzzy mapping of factor set (indicator set) \( U \) to \( F(V) \) is established, and single factor evaluation set \( R_i \) and single factor evaluation matrix \( R \) are constructed. The fuzzy mapping from \( U \) to \( F(V) \) is:

\[
f: U \rightarrow F(V), \forall u_i \in U, u_i \rightarrow f(u_i) = \frac{r_{i1}}{v_1} + \frac{r_{i2}}{v_2} + \cdots + \frac{r_{i5}}{v_5}
\]

Where \( r_{ij} \) represents the degree of membership of \( u_i \) to \( v_j \). According to the function of the fuzzy mapping, the single-factor evaluation set \( R_i \) and the Single-factor evaluation matrix \( R = (r_{ij})_{n \times m} \) is established.

3.4 Fuzzy Comprehensive Evaluation

(1) First level comprehensive evaluation

According to the index weight vector \( C(\omega_i) \) and the single factor evaluation matrix \( R \), the criterion-level fuzzy evaluation vector \( B_i \) is calculated, and the second-level criterion-level evaluation matrix \( B = (B_1, B_2, \ldots, B_5) \) is formed by the subset \( B_i \).

(2) Second level comprehensive evaluation

In the same way, \( C = B(\omega_i) \cdot B \). Where \( C \) is the comprehensive evaluation vector of the sponge road traffic system, \( B(\omega_i) \) is the criterion-level weight vector. According to the principle of maximum membership degree, the maximum value of vector \( C \) is taken as the evaluation result of the sponge road traffic system.

4. Case Study

4.1 Index Weight Calculation

The 1-9 scale method is used to compare the relative importance of various factors at the same level, and a judgment matrix is established. the maximum eigenvalue \( \lambda_{max} \) and its normalized eigenvector
\( \omega_i \) is solved. \( \omega_i \) is the weight of each influencing factor in the same layer. The calculation results are shown in the table below.

### Table 1. The weight of criterion level matrix

| A | B     | C     | weight |
|---|-------|-------|--------|
| A | 1/2   | 1/3   | 0.16   |
| B | 1     | 1/3   | 0.25   |
| C | 3     | 1     | 0.59   |

Consistency check:
\( \lambda_{max} = 3.05; \ CI = 0.03; \ RI = 0.05 \)

### Table 2. The weight of judgment matrix A

| A   | A11 | A12 | A13 | A14 | weight |
|-----|-----|-----|-----|-----|--------|
| A11 | 1   | 3   | 5   | 3   | 0.51   |
| A12 | 1/3 | 1   | 1/3 | 2   | 0.23   |
| A13 | 1/5 | 1/3 | 1   | 1/4 | 0.07   |
| A14 | 1/3 | 1/2 | 4   | 1   | 0.19   |

Consistency check:
\( \lambda_{max} = 4.16; \ CI = 0.05; \ RI = 0.06 \)

### Table 3. The weight judgment matrix B

| B   | B11 | B12 | B13 | B14 | weight |
|-----|-----|-----|-----|-----|--------|
| B11 | 1   | 1/2 | 4   | 3   | 0.26   |
| B12 | 2   | 1   | 7   | 5   | 0.47   |
| B13 | 1/4 | 1/7 | 1   | 1/2 | 0.06   |
| B14 | 1/3 | 1/5 | 2   | 1   | 0.10   |
| B15 | 1/3 | 1/5 | 3   | 1   | 0.11   |

Consistency check:
\( \lambda_{max} = 5.09; \ CI = 0.02; \ RI = 0.02 \)

### Table 4. The weight of judgment matrix C

| C   | C11 | C12 | C13 | C14 | weight |
|-----|-----|-----|-----|-----|--------|
| C11 | 1   | 3   | 2   | 4   | 0.47   |
| C12 | 1/3 | 1   | 1/2 | 2   | 0.16   |
| C13 | 1/2 | 2   | 1   | 3   | 0.28   |
| C14 | 1/4 | 1/2 | 1/3 | 1   | 0.10   |

Consistency check:
\( \lambda_{max} = 4.03; \ CI = 0.01; \ RI = 0.01 \)

#### 4.2 Fuzzy Comprehensive Evaluation Matrix

The index level elements are scored by the expert scoring method, the membership degree of each element relative to the comment level is determined, and the single-factor evaluation matrix \( R \) as follows.

\[
R_A = \begin{bmatrix}
0.00 & 0.620 & 0.21 & 0.17 & 0.00 \\
0.23 & 0.440 & 0.17 & 0.16 & 0.00 \\
0.11 & 0.26 & 0.45 & 0.18 & 0.00 \\
0.17 & 0.150 & 0.21 & 0.17 & 0.00 \\
\end{bmatrix}
\]

\[
R_B = \begin{bmatrix}
0.09 & 0.36 & 0.39 & 0.16 & 0.00 \\
0.21 & 0.12 & 0.46 & 0.21 & 0.00 \\
0.15 & 0.32 & 0.27 & 0.26 & 0.00 \\
0.08 & 0.39 & 0.24 & 0.20 & 0.09 \\
0.12 & 0.38 & 0.22 & 0.20 & 0.08 \\
\end{bmatrix}
\]

\[
R_C = \begin{bmatrix}
0.10 & 0.44 & 0.27 & 0.19 & 0.00 \\
0.09 & 0.30 & 0.25 & 0.36 & 0.00 \\
0.15 & 0.41 & 0.32 & 0.12 & 0.00 \\
0.05 & 0.24 & 0.38 & 0.33 & 0.00 \\
\end{bmatrix}
\]

(1) First-level comprehensive evaluation

\[
R_A^* = [0.53 \ 0.23 \ 0.07 \ 0.19] \times R_A = [0.09 \ 0.52 \ 0.22 \ 0.17 \ 0.00] \\
R_B^* = [0.26 \ 0.47 \ 0.06 \ 0.10 \ 0.00] \times R_B = [0.15 \ 0.25 \ 0.38 \ 0.20 \ 0.02] \\
R_C^* = [0.47 \ 0.16 \ 0.28 \ 0.04] \times R_C = [0.11 \ 0.39 \ 0.29 \ 0.21 \ 0.00] \\
\]

(2) The second level comprehensive evaluation

Single-factor evaluation matrix: \( R^* = [R_A^* \ R_B^* \ R_C^*] \). The criterion-level index weight is: [0.16 0.25 0.59]. The second-level comprehensive evaluation results of the sponge-type road traffic system: \( B^* = [0.16 \ 0.25 \ 0.59] \times R^* = [0.12 \ 0.38 \ 0.30 \ 0.20 \ 0.01] \). \( B^* \) is the relative membership degree of the review set \( V \) of the sponge-type road traffic system. According to the principle of maximum membership degree, the sponge-type road traffic system is generally in good condition.
5. Conclusion
The sponge-type road traffic system accurately evaluates the stability and robustness of the urban sponge-type road traffic system and measures the development level of urban traffic infrastructure. This paper constructs a sponge road traffic system evaluation system from three levels of adaptability, technicality, and operability, and applies the fuzzy analytic hierarchy process to evaluate the operation effect of the sponge road traffic system. The results show that the sponge road traffic system in the study area is in good condition and exists in a certain room.

6. Acknowledgements
It is supported by Natural Science of Zhejiang Province (No. LY18G030021 & No. LY18G010009) and Education Department of Zhejiang Province (No. Y201738488).

7. References
[1] Lu H P. 2012 Study on urban traffic supply strategy and Traffic Demand Management Strategy. Urban Transport, chapter 10(03) pp 1-6
[2] Han C Y, et al. 2019 Evaluating the Spatial Deprivation of Public Transportation Resources in Areas of Rapid Urbanization: Accessibility and Social Equity. D D in N & S p 1-11
[3] Sun Q X, et al. 2019 Research on traffic congestion characteristics of city business circles based on TPI data: The case of Qingdao, China. Physica A: S M &A p 534
[4] Yang W J, et al. 2020 Evaluation of urban traffic noise pollution based on noise maps. TRP p 87
[5] Li Y X, et al. 2020 Analyzing traffic violation behavior at urban intersections: A spatio-temporal kernel density estimation approach using automated enforcement system data. AAP p 141
[6] K B, et al. 2020 Human factors contributing to the road traffic accident occurrence. TRP p 45
[7] Rao A M, et al. 2012 Measuring Urban Traffic Congestion – A Review. IJTTE, chapter 2(4) pp 286-305
[8] A C M, et al. 2018 Transport Planning and Traffic Engineering. CRC Press
[9] Brown T, et al. 2004 Assessing infrastructure interdependencies: the challenge of risk analysis for complex adaptive systems. IJCI chapter 1 pp 108-117
[10] Schade W, et al. 2001 Strategic sustainability analysis: broadening existing assessment approaches for transport policies. TRR chapter 1756(1) pp 3-11
[11] Shinya K, et al. 2002 Applicability of an agent-based modeling concept to modeling of transportation phenomena. YJOR chapter 12(2) pp 141-156
[12] Giannakodakis, G. 994 Transport planning: a holistic systems approach. RTR chapter 3 pp4–20
[13] Zachariadis T. 2005 Assessing policies towards sustainable transport in Europe: an integrated model. EP, chapter 33(12) pp 1509-1525
[14] Targa F, et al. 2005 Economic activity and transportation access: an econometric analysis of business spatial patterns. TRR, chapter 1932(1) pp 61-71
[15] Prades J A, et al. 2003 Societal integration and sustainable transportation: testing an adaptive approach. E&SD, pp 593-602
[16] Liu H Q. 2005 Study on evaluation system of Trunk Highway Network Development Adaptability in urbanization process. Nanjing: Southeast University
[17] Guo H. 2005 Theoretical analysis on adaptability of Regional Highway Network Developmen. Xi’an: Chang an University
[18] Pan W. 2008 GA adaptability analysis of highway network structure in urban agglomeration. Xi’an: Chang an University
[19] Xu J. 2010 Research on the integrated development mechanism of urban land use and transportation. TST chapter (04) pp 89-92
[20] Mathur S. 2019 An evaluative framework for examining the use of land value capture to fund public transportation projects. LUP, chapter 86 pp 357-364
[21] Liu H Q. 2005 Research on the Adaptability Evaluation System of Arterial Highway Network Development in the Process of Urbanization. Southeast University
[22] Shi Y Z, et al. 1995 Research on Technical Evaluation Index and Evaluation Standard of Highway Network Planning. *CJHT* pp 120-124

[23] Wang W. 2008 Traffic Engineering. M. *Nanjing: Southeast University Press*

[24] Sun R. 2008 Study on road traffic planning of Industrial Park. *Xi'an University of Architecture and Technology*

[24] Hu J Z. 1989 Ambiguity and decision support system. *Wuhan: Central China Normal University*

[25] Li L. 2013 Study on operational efficiency evaluation of urban road traffic network. *Changsha University of Science and Technology*

[26] Peng L. Study on 2005 Evaluation Index System and implementation decision method of Highway Network Planning. *Southeast University*