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Assessment of Urban Mobility via a Pressure-State-Response (PSR) Model with the IVIF-AHP and FCE Methods: A Case Study of Beijing, China

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Abstract: Urban transportation issues continue to emerge and evolve as a result of rapid urbanization, and the systematic and scientific assessment of urban mobility is becoming increasingly essential. In this work, a Pressure-State-Response (PSR) model with 25 indicators was established to reflect the status of urban mobility. Then, the importance of indicators was determined with the interval-valued intuitionistic fuzzy analytic hierarchy process (IVIF-AHP) method, and the fuzzy comprehensive evaluation (FCE) method was applied to assess the overall status of urban mobility. The validity of the proposed model was demonstrated using the mobility system of Beijing as a case study, and the pressure, state, and response scores were calculated. The proposed assessment model can help to improve urban transportation monitoring and can also provide a scientific foundation for future urban transportation policymaking, planning, and traffic management, thereby further ensuring the sustainable development of urban transportation systems.

Keywords: urban mobility assessment; MCDM; IVIF-AHP; fuzzy comprehensive evaluation; urban transport; quantified analysis

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1. Introduction

The rate of urbanization is increasing, resulting in a slew of issues such as urban population growth, energy pollution, and transportation congestion [1–4]. Urban mobility plays a critical role in urban development, and the disparity between the urban transit supply and massive traffic demand is becoming increasingly severe [5,6]. Due to external pressures such as increases in the number of private vehicles and the urban population, public satisfaction with urban transportation is dwindling. Undoubtedly, a more sustainable urban mobility system will be beneficial not only for the satisfaction of urban residents, but also for the economic development of cities [7–9]. Furthermore, urban mobility assessment is necessary for monitoring the status of urban mobility systems, providing a foundation for the scientific management and sustainable development of urban transportation.

Methods for the assessment of passenger satisfaction, public transit accessibility, the sustainability of urban transport systems, etc., have been popular research topics in recent years, and numerous related studies have been published [10–13]. Nevertheless, overall urban mobility assessment should consider more factors influencing urban mobility systems themselves, as well as other human, social, and economic environments. Therefore, related assessment models should be scientific, methodical, representational, and simple to apply.

The Organization for Economic Co-operation and Development [14] developed the Pressure-State-Response (PSR) theoretical framework to structure its work on environmental policy and reporting, which may include several categories such as social economy, the natural environment, and human activities [15]. The PSR model is a systematic and complete assessment model that can incorporate numerous impact elements. As a result, the model is a suitable technique for the analysis of complex systems, such as ecosystems and water resource systems [16,17]. To construct an index system for the analysis of urban mobility in this study, this method is first introduced. In the PSR model, pressure indicators reflect external pressure on urban mobility, state indicators represent the current state of urban mobility, and response indicators represent the activities taken by the administrative department to alleviate pressure and enhance the mobility state. The PSR model can clearly depict the links between pressure, state, and response during this process.

Due to the complexity and diversity of the indexes, the multiple-criteria decision-making (MCDM) approach is an appropriate instrument for the evaluation of urban mobility. MCDM is an effective technique that is used in a variety of fields, including the environment, management, transportation, and logistics fields, to resolve complicated problems that involve several decision-makers (DMs), criteria, and objectives [18]. The method can be used to provide an overall evaluation of a system by qualitatively and quantitatively measuring the criteria of each of the DMs [19]. Nevertheless, decision-making processes are based on human perception, which creates uncertainty. Thus, to minimize complexity and uncertainty, standard MCDM approaches must be adapted to a fuzzy environment. Therefore, the concept of fuzziness has been widely used to simulate uncertainty in real-world circumstances. In the transportation field, MCDM techniques and fuzzy set theory have been used in recent decades for the evaluation and initiation of decision-making, as summarized in Table 1.

Table 1. The usage of the MCDM method in the transportation field.

Techniques Used	Problem	Authors
Fuzzy AHP	Budget allocation for transportation infrastructure construction	Teng et al., 2009 [20]
	Investigation of the pandemic's impact on the quality of public transportation services	Alkharabsheh and Duleba, 2021 [21]
Fuzzy TOSIS	Assessment of sustainable transport solutions	Awasthi et al., 2011 [22]
ANP	Selection of road transport projects	Ivanović et al., 2013 [23]
	Risk assessment of large-scale transportation infrastructure	Yucelgazi and Yitmen, 2018 [24]
VIKOR and interval type-2 fuzzy sets	Rail transit customer satisfaction assessment	Celik et al., 2014 [25]
Entropy and TOPSIS	Assessment of the sustainable development of the highway transportation capacity	Li et al., 2014 [26]
VIKOR with fuzzy set theory	Selection of hazardous industrial waste transportation firms	Kabir, 2015 [27]
Delphi ANP, GAHP and PROMETHEE	Assessment of public transport systems in Tehran	Nassereddine and Eskandari, 2017 [28]
IAHP	Sustainable urban transport planning considering different stakeholder groups	Ghorbanzadeh et al., 2018 [29]
AHP, Fuzzy TOPSIS	Suitable transport project selection for more urban livability	Hamurcu and Eren, 2020 [30]
Best worst method	Finding alternative mobility modes after COVID-19	Moslem et al., 2020 [31]
	Determining optimal locations of bicycle sharing system stations and cycling infrastructure	Guler and Yomralioglu, 2021 [32]

The purpose of this research is to address insufficient information and uncertain factors in the analysis of urban mobility assessment. The interval-valued intuitionistic fuzzy analytic hierarchy process (IVIF-AHP) approach is used to reduce the ambiguity of experts in decision-making. Moreover, fuzzy comprehensive evaluation (FCE) is utilized to comprehensively consider all weighted indicators when calculating the final evaluation score. The contributions of this article include the following: (1) the gap in the existing literature is introduced and an urban mobility assessment model under the PSR framework is presented; (2) new dimensions and evaluation criteria for urban mobility assessment are identified and categorized; (3) the IVIF-AHP and FCE methods are applied to improve the overall accuracy of urban mobility assessment.

The remainder of this article is organized as follows. In Section 2, a detailed literature review is provided. Section 3 is devoted to the introduction of the PSR indicators and the two-stage approach, including the IVIF-AHP and FCE methods. The proposed methodology is then applied to a real case study in Beijing in Section 4. The results analysis and discussion are then presented in Section 5, and the conclusion of this study is provided in Section 6.

2. Literature Review

2.1. Urban Mobility Assessment

Urban mobility describes the movement of people between diverse origins and destinations in varying time periods and using various modes of transportation and travel to achieve different goals. Several researchers have examined urban mobility from a variety of perspectives, including the analysis of the complex relationship between urban sprawl and displacement via the use of a mobility impact index [33]; the analysis of the mobility of residents, including the elderly, in Canadian metropolitan areas [34]; the identification of problems and the proposal of solutions to reduce car use [35]; and the definition of the various types of urban development and their relationships [36]. For the assessment of urban mobility, Hüging et al. [37] examined existing evaluation methodologies for urban mobility assessment, as well as their benefits, limitations, and potential application to a variety of urban mobility measures. Regmi [38] used four Asian cities as experimental cases for the assessment of urban mobility. Šoštarić et al. [39] described the creation of a data-driven framework for the assessment and improvement of sustainable urban mobility.

2.2. IVIF-AHP

Since the AHP was first proposed, it has been one of the most extensively used methods in the solution of MCDM problems [40,41]. The main benefit of the AHP is that it can be used to analyze the consistency of a DM's judgments. Additionally, the AHP can assist DMs in organizing the many assessment components of an issue into a hierarchical structure, thereby simplifying the decision-making process [42]. As a result, the AHP has been widely implemented in a number of transportation studies, including those related to traffic management [43–46], spatial decisions systems [47,48], and risk assessment for construction projects [49,50]. However, urban mobility is closely linked to the environment, economy, people, and policymaking of a city, which together represent a complex system [51]. Due to the ambiguity of DMs caused by varying perceptions of their own interests without regard for the interests of other diverse groups, the classical AHP inevitably oversimplifies complex systems [52].

To eliminate the subjectivity of DMs, intuitionistic fuzzy sets (IFSs) were developed. IFSs include the degrees of non-membership, membership, and hesitation, thereby allowing them to handle more flexible and imprecise data than conventional fuzzy sets [53]. Later, interval-valued intuitionistic fuzzy sets (IVIFSs) were coupled with the AHP by defining every single lower and upper bound of the membership, non-membership, and hesitation degree functions, rather than precise numbers, to further adapt to the uncertainty of experts' judgment. The advantage of IVIF-AHP is that it allows for the hierarchical construction of major and sub-indicators and the calculation of their weights [54]. This method has been introduced in the transportation field to evaluate the quality of public transportation services [55], the sustainability of public transportation [56], the selection of corridors for locating autonomous vehicles [57], and the location selection of electric vehicle charging stations [58].

2.3. FCE

The FCE technique is based on fuzzy mathematics and utilizes the principle of fuzzy relationship synthesis to quantify aspects that are not explicitly quantifiable, as well as to completely evaluate the membership status of the evaluated object based on multiple factors [59]. Due to the uncertainty inherent in the evaluation process, experts are more confident when employing fuzzy judgment rather than crisp comparisons. FCE is widely employed in a variety of fields, including ecology [60,61], engineering [62,63], and business [64]. Additionally, it is frequently used in decision-making and evaluation processes involving complex transportation systems and inexact transportation problems, such as in the assessment of passenger satisfaction with public transportation [65], the assessment of the vulnerability of highway transportation systems [66], and the evaluation of the safety resilience of public buses [67]. The contribution of FCE in the present research is to comprehensively consider the related indicators according to the weighted indicators from IVIF-AHP and to obtain the final status score of urban mobility.

3. Methodology

The purpose of this research was to develop a three-step evaluation system for urban transportation. To begin, an assessment index system comprising pressure, state, and reaction indicators was constructed and quantified to measure urban mobility. Then, the IVIF-AHP approach was used to determine the weight of each pressure, state, and reaction indicator. Finally, the FCE method was utilized to quantify the overall urban mobility performance with the corresponding multiple factors. The methodological framework is illustrated in Figure 1.

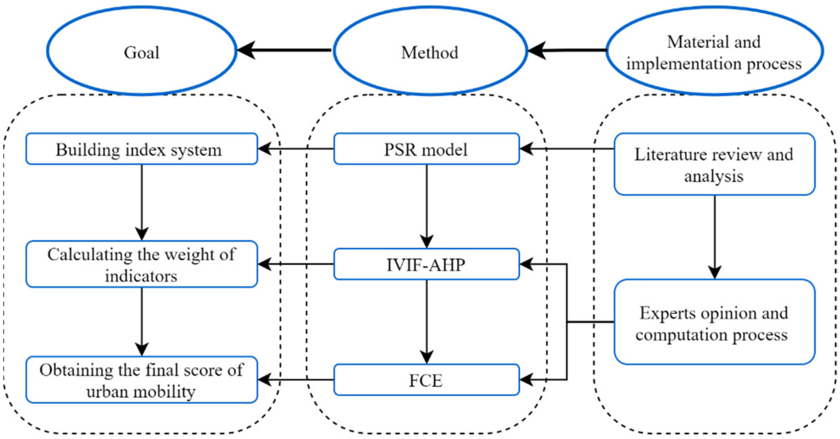

Figure 1. The proposed methodological framework for urban mobility assessment.

3.1. Establishment of an Index System with the PSR Model

The fundamental principle of the PSR model is that the various production and management activities conducted by the city for its own growth exert either a positive or negative influence (pressure) on the environment of sustainable development. In response to pressure, the government or social groups take action to adapt, which, in turn, represses pressure while changing the state of the system; this establishes strong relationships via the "pressure-state-response" cycle. The PSR relationships in the PSR model are illustrated in Figure 2 [68]. In this research, an index system for the evaluation of urban mobility systems was first developed using this model.

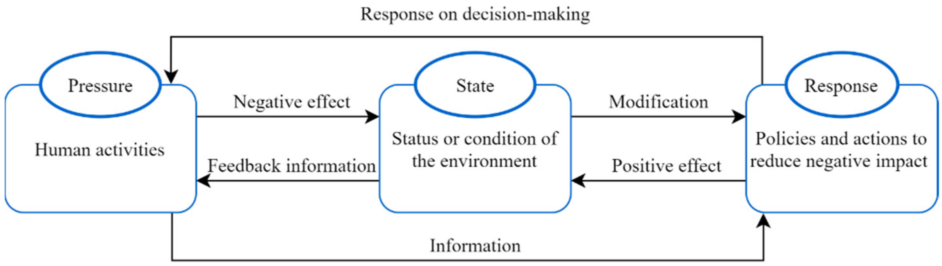

Figure 2. Relationships in the PSR model.

The proposed urban mobility PSR index system serves the following three purposes: (i) to describe and represent the sustainable development status of the economy, population, environment, resources, and urban mobility at any moment in time or over a period of time; (ii) to assess the changes in urban mobility during a specific time period; (iii) to verify the connection between the urban mobility system and other areas. The index system is presented in Table 2. The index system comprised three layers—namely, the criteria layer, the factor layer, and the indicator layer. The criteria system was divided into three subsystems—namely, pressure criteria layer, state criteria layer, and response criteria layer.

The pressure criteria layer is used to identify the source of changes in the urban mobility system caused by human activity or the city itself. Most cities are currently undergoing rapid urbanization, which has resulted in the increase in the population and urban area growth. Additionally, the increase in the number of private cars and an unreasonable urban structure increase the severity of congestion. Therefore, four indicators relating to population increases, the increase in the number of private cars, urban area growth, and unreasonable urban structures were selected.

The state criteria layer is used to describe and reflect the status of the urban mobility system, which can be divided into three factor layers. Public transportation is a popular alternative to driving a private vehicle, and numerous factors motivate people to use it. The bus travel speed, and the punctuality of public transport were selected to reflect the effectiveness of the public transport system, while the density levels of public transport routes and stations were used to reflect accessibility. The social environment of giving preference to travel via public transportation was selected to assess the priority level from a macro perspective. In terms of non-motorized traffic, convenience and safety are the two key factors. The pedestrian walkway setting level, the density level of the bicycle network, and the supply and demand matching performance of shared bikes were chosen to reflect the accessibility and effectiveness of the system, and the partition between motor vehicles and non-motorized traffic was selected to reflect safety. In terms of personalized travel, the average travel speed of private vehicles during peak hours and the level of congestion duration of private vehicles on weekdays were chosen to reflect the congestion condition. Furthermore, the supply capacity of parking spaces was another influencing factor that was chosen to reflect the supply capacity of a personalized travel environment. With the increasing proportion of online car-hailing used for personalized travel, the average response speed of taxi and online car-hailing was selected to assess the efficiency of the traveler.

The response criteria layer is used to reflect efforts to resolve urban mobility problems. To improve urban mobility, the improvement of traffic management, policy and regulations is necessary. Additionally, as electrification, intelligence, and ride-sharing are key trends of urban transportation, three corresponding indicators were selected.

Table 2. The index system for urban mobility.

Criteria Layer	Factor Layer	Indicator Layer	Indicator Source
Pressure (C_1)		The pressure of population growth (I_1)	Solé-Ribalta et al., 2016 [69]
		The pressure of private vehicle ownership growth (I_2)	Hao et al., 2011 [70]
		The pressure of urban area growth (I_3)	Banister, 2011 [71]
		The pressure of an unreasonable urban structure (I_4)	Ahmed et al., 2008 [72]
State (C_2)	Public transport (F_1)	Density level of public transport routes (I_5)	Wong et al., 2017 [73]
		Bus travel speed during peak hours (I_6)	Hu and Shalaby, 2017 [74]
		Social environment of giving preference to public transportation travel (I_7)	Jain et al., 2014 [75]
		Punctuality of public transport (I_8)	Yaakub and Napiah, 2011 [76]
		Connection performance between urban transit and other modes (I_9)	Di et al., 2016 [77]
		Density level of urban public transportation stations (I_{10})	Chica-Olmo et al., 2018 [78]
	No-motorized traffic (F_2)	Social environment of giving preference to non-motorized travel (I_{11})	Raha and Taweesin, 2013 [79]
		Pedestrian walkway setting level (I_{12})	Kasemsuppakorn and Karimi, 2013 [80]
		Density level of the bicycle network (I_{13})	Szell et al., 2021 [81]
		Supply and demand matching performance of shared bikes (I_{14})	Song et al., 2021 [82]
		The partition between motor vehicles and non-motorized traffic (I_{15})	Bai and Chen, 2019 [83]
	Personalized travel (F_3)	Average travel speed of private vehicles during peak hours (I_{16})	Hitge and Vanderschuren, 2015 [84]
		Congestion duration level of private vehicles on weekdays (I_{17})	Chakrabarti, 2017 [85]
		Supply capacity of parking spaces (I_{18})	Simićević et al., 2013 [86]
		Convenience level of car rental (I_{19})	Berg et al., 2019 [87]
		Average response speed of taxis and online car-hailing (I_{20})	Nguyen-Phuoc et al., 2020 [88]
Response (C_3)		Improvement of urban traffic management (I_{21})	Torrisi et al., 2018 [89]
		Improvement of urban transport policy and regulations (I_{22})	May, 2015 [90]
		Improvement of urban transport intelligence and informatization (I_{23})	Nikitas et al., 2020 [91]
		The policy of supporting clean energy and new-energy vehicles (I_{24})	Van et al., 2012 [92]
		Improvement of regulating and monitoring the service of taxis and online car-hailing (I_{25})	Lyn et al., 2021 [93]

3.2. Determination of Indicator Weights with IVIF-AHP

3.2.1. Preliminaries of IF and IVIF Sets

As introduced previously, IFSs include the degree of non-membership, membership, and hesitation. Let M be a non-empty set, and let Equation (1) be an intuitionistic fuzzy set where $\mu_{\widetilde{A}}(x)$ and $\nu_{\widetilde{A}}(x)$ are, respectively, the degrees of membership and non-membership of element x belonging to Q: $\mu_{\widetilde{A}} : x \to [0,1]$, $\nu_{\widetilde{A}} : x \to [0,1]$. The relationship between $\mu_{\widetilde{A}}$ and $\nu_{\widetilde{A}}$ is determined by Equation (2). Additionally, $\pi_{\widetilde{A}}$ is related to the hesitation degree of x, which is a property of A; it is calculated by Equation (3).

$$A = \{\langle x, \mu_{\widetilde{A}}(x), \nu_{\widetilde{A}}(x)\rangle | x \in Q\} \tag{1}$$

$$0 < \mu_{\widetilde{A}}(x) + \nu_{\widetilde{A}}(x) < 1 \tag{2}$$

$$\pi_{\widetilde{A}}(X) = 1 - \mu_{\widetilde{A}}(x) - \nu_{\widetilde{A}}(x) \tag{3}$$

By using the concepts of IFSs [94,95] and IVIFSs [96], a method for the construction of the membership functions of an IVIFS from the given membership functions of an IFS was previously proposed by [97]. Assume that $A \in IFS(x)$, $X \to [0,1] \times [0,1]$ and $x \to (\alpha_x + \beta_x)$, such that $\alpha_x, \beta_x \in [0,1]$ and $0 \leq \alpha_x + \beta_x \leq 1$; if $\pi_{\widetilde{A}}(X) \neq 0$, then α_x and β_x satisfy $\alpha_x \leq \mu_{\widetilde{A}}(x)$ and $\beta_x \leq \nu_{\widetilde{A}}(x)$. If $\pi_{\widetilde{A}}(X) = 0$, then $\alpha_x = 0$ and $\beta_x = 0$. If $\alpha_x + \beta_x \in [0,1]$, then $\alpha_x = 0.5$ and $\beta_x = 0.5$ are chosen as the fuzzy coefficients, and Equations (4)–(7) are obtained.

$$\mu^L_{\widetilde{A}}(x) = |\mu_{\widetilde{A}}(x) - \alpha_x \pi_{\widetilde{A}}(x)| \tag{4}$$

$$\mu^U_{\widetilde{A}}(x) = |\mu_{\widetilde{A}}(x) + \alpha_x \pi_{\widetilde{A}}(x)| \tag{5}$$

$$\nu^L_{\widetilde{A}}(x) = |\mu_{\widetilde{A}}(x) - \beta_x \pi_{\widetilde{A}}(x)| \tag{6}$$

$$\nu^U_{\widetilde{A}}(x) = |\mu_{\widetilde{A}}(x) + \beta_x \pi_{\widetilde{A}}(x)| \tag{7}$$

Moreover, $\pi^L_{\widetilde{A}}$ and $\pi^U_{\widetilde{A}}$ can, respectively, be obtained by Equations (8) and (9).

$$\pi^L_{\widetilde{A}}(x) = 1 - \mu^U_{\widetilde{A}}(x) - \nu^U_{\widetilde{A}}(x) \tag{8}$$

$$\pi^U_{\widetilde{A}}(x) = 1 - \mu^L_{\widetilde{A}}(x) - \nu^L_{\widetilde{A}}(x) \tag{9}$$

For simplicity, the lower and upper bounds of the IVIFS are denoted by Equation (10).

$$\widetilde{A} = [\mu^L_{\widetilde{A}}, \mu^U_{\widetilde{A}}], [\nu^L_{\widetilde{A}}, \nu^U_{\widetilde{A}}], [\pi^L_{\widetilde{A}}, \pi^U_{\widetilde{A}}] \tag{10}$$

3.2.2. Calculation Procedure of the IVIF-AHP Method

Step 1: Collection of the experts' opinions of each other to assess the weights of DMs.

DM_j denotes DM J, $J = 1, 2, \ldots, j$. Table 3 presents the linguistic terms used to assess the weights of DMs. Via the use of Table 3, DMs are asked to provide their opinions of other DMs. The weights of DMs are calculated with the interval-valued intuitionistic fuzzy weighted averaging (IIFWA) operator proposed by Xu and Cai [98]. The judgments of DMs are aggregated by Equations (11)–(14), and the aggregated results are then used to determine the weights of DMs via Equation (15).

$$\mu^{(j)}_{\widetilde{A}} = \left[1 - \prod_{j=1}^{J}\left(1 - \mu^L_{\widetilde{A}}\right)^{\lambda^*}, 1 - \prod_{j=1}^{J}\left(1 - \mu^U_{\widetilde{A}}\right)^{\lambda^*}\right] \tag{11}$$

$$\nu^{(j)}_{\widetilde{A}} = \left[\prod_{j=1}^{J}\left(\nu^L_{\widetilde{A}}\right)^{\lambda^*}, \prod_{j=1}^{J}\left(\nu^U_{\widetilde{A}}\right)^{\lambda^*}\right] \tag{12}$$

$$\pi^{L(j)}_{\widetilde{A}} = \prod_{j=1}^{J}\left(1 - \mu^U_{\widetilde{A}}\right)^{\lambda^*} - \prod_{j=1}^{J}\left(\nu^U_{\widetilde{A}}\right)^{\lambda^*} \tag{13}$$

$$\pi_{\widetilde{A}}^{U(j)} = \prod_{j=1}^{J}\left(1-\mu_{\widetilde{A}}^{L}\right)^{\lambda^*} - \prod_{j=1}^{J}\left(\nu_{\widetilde{A}}^{L}\right)^{\lambda^*} \tag{14}$$

$$\lambda^j = \frac{\sqrt{\frac{1}{2}\left[\left(1-\pi_{\widetilde{A}}^{L(j)}\right)+\left(1-\pi_{\widetilde{A}}^{U(j)}\right)\right]}}{\sum_{j=1}^{J}\sqrt{\frac{1}{2}\left[\left(1-\pi_{\widetilde{A}}^{L(j)}\right)+\left(1-\pi_{\widetilde{A}}^{U(j)}\right)\right]}} \tag{15}$$

In Equations (11)–(15), $\lambda^* = \frac{1}{J-1}$ and λ^j is the weight of the j^{th} DM.

Table 3. The linguistic terms for the weights of DMs [99].

Linguistic Variable	IVIF Values		
	$[\mu_{\widetilde{A}}^{L},\mu_{\widetilde{A}}^{U}]$	$[\nu_{\widetilde{A}}^{L},\nu_{\widetilde{A}}^{U}]$	$[\pi_{\widetilde{A}}^{L},\pi_{\widetilde{A}}^{U}]$
Very qualified (VQ)	[0.95,1.00]	[0.00,0.00]	[0.00,0.05]
Qualified (Q)	[0.80,0.85]	[0.05,0.10]	[0.05,0.15]
Relatively qualified (RQ)	[0.60,0.65]	[0.10,0.15]	[0.20,0.30]
Relatively less qualified (RLQ)	[0.30,0.35]	[0.25,0.30]	[0.35,0.45]
Less qualified (LQ)	[0.20,0.25]	[0.30,0.35]	[0.40,0.50]
Very less qualified (VLQ)	[0.00,0.05]	[0.45,0.50]	[0.45,0.55]

Step 2: Collection of the assessment table of each layer from the opinions of DMs.

To construct a matrix of pairwise IVIF value comparisons, DMs score the ratings for each indicator according to the linguistic terms listed in Table 4

Table 4. The linguistic terms for the evaluation of indicators [97].

Preference on Comparison	IVIF Values	Reciprocal IVIF Values
	$[\mu_{\widetilde{A}}^{L},\mu_{\widetilde{A}}^{U}]$, $[\nu_{\widetilde{A}}^{L},\nu_{\widetilde{A}}^{U}]$, $[\pi_{\widetilde{A}}^{L},\pi_{\widetilde{A}}^{U}]$	$[\mu_{\widetilde{A}}^{L},\mu_{\widetilde{A}}^{U}]$,$[\nu_{\widetilde{A}}^{L},\nu_{\widetilde{A}}^{U}]$,$[\pi_{\widetilde{A}}^{L},\pi_{\widetilde{A}}^{U}]$
Equally important (EI)	[0.38,0.42], [0.22,0.58], [0,0.4]	[0.22,0.58], [0.38,0.42], [0,0.4]
Equally very important (EVI)	[0.29,0.41], [0.12,0.58], [0.01,0.59]	[0.12,0.58], [0.29,0.41], [0.01,0.59]
Moderately important (MI)	[0.10,0.43], [0.03,0.57], [0,0.87]	[0.03,0.57], [0.10,0.43], [0,0.87]
Moderately more important (MMI)	[0.03,0.47], [0.03,0.53], [0,0.94]	[0.03,0.53], [0.03,0.47], [0,0.94]
Strongly important (SI)	[0.13,0.53], [0.07,0.47], [0,0.8]	[0.07,0.47], [0.13,0.53], [0,0.8]
Strongly more important (SMI)	[0.32,0.62], [0.08,0.38], [0,0.6]	[0.08,0.38], [0.32,0.62], [0,0.6]
Very strongly more important (VSMI)	[0.52,0.72], [0.08,0.28], [0,0.4]	[0.08,0.28], [0.52,0.72], [0,0.4]
Extremely strong important (ESI)	[0.75,0.85], [0.05,0.15], [0,0.2]	[0.05,0.15], [0.75,0.85], [0,0.2]
Extremely more important (EMI)	[1,1], [0,0], [0,0]	[0,0], [1,1], [0,0]

Step 3: Calculation of the aggregated IVIF values and group IVIF values.

According to the DMs' assessments, the IIFWA operator given by Equations (16)–(19) is used to compute the IVIF values of each indicator [98]. Then, the group IVIF values are calculated by the IVIF values based on the weights of the DMs.

$$\mu_{\widetilde{A}_k} = \left[1 - \prod_{j=1}^{J}\left(1 - \mu_{\widetilde{A}}^{L}\right)^{\lambda^j}, 1 - \prod_{j=1}^{J}\left(1 - \mu_{\widetilde{A}}^{U}\right)^{\lambda^j}\right] \tag{16}$$

$$\nu_{\widetilde{A}_k} = \left[\prod_{j=1}^{J}\left(\nu_{\widetilde{A}}^{L}\right)^{\lambda^j}, \prod_{j=1}^{J}\left(\nu_{\widetilde{A}}^{U}\right)^{\lambda^j}\right] \tag{17}$$

$$\pi_{\widetilde{A}_k}^{L} = \prod_{j=1}^{J}\left(1 - \mu_{\widetilde{A}}^{U}\right)^{\lambda^j} - \prod_{j=1}^{J}\left(\nu_{\widetilde{A}}^{U}\right)^{\lambda^j} \tag{18}$$

$$\pi_{\widetilde{A}_k}^{U} = \prod_{j=1}^{J}\left(1 - \mu_{\widetilde{A}}^{L}\right)^{\lambda^j} - \prod_{j=1}^{J}\left(\nu_{\widetilde{A}}^{L}\right)^{\lambda^j} \tag{19}$$

In Equations (16)–(19), $\sum_{j=1}^{J} \lambda^j = 1$.

Step 4: Calculation of the consistency ratio.

The calculation of the consistency ratio (CR) during the IVIF-AHP process was developed from the original concept proposed by Saaty [40]. The CR can be calculated using Equation (20) and the random index (RI) presented in Table 5. If the CR value is less than or equal to 0.10, it is considered receivable; otherwise, the assessment of DMs should be considered inconsistent, and opinions should be gathered once more.

$$CR = \frac{RI - \frac{\sum \pi_{A_k}^{U}(x)}{n}}{n-1} \tag{20}$$

where n is the number of matrix elements and $\pi_{A_k}^{U}(x)$ is the hesitation value.

Table 5. The random index [40].

n	1–2	3	4	5	6	7	8	9
RI	0.0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

Step 5: Calculation of the indicator weights.

The weight vectors $v_1, v_2, \cdots, v_n$, with $v_k \geq 0, k = 1, 2, \cdots, n$ and $\sum_{k=1}^{n} V_k = 1$, are determined, and indicate the relative importance of various indicators in each layer. The crisp indicator weights are calculated by Equations (21) and (22) [100].

$$V_k = \frac{1 - \widetilde{V}_k}{n - \sum_{k=1}^{n} \widetilde{V}_k} \tag{21}$$

$$\widetilde{V}_k = 1 - \frac{\sum_{j=1}^{J} \frac{\lambda^{(j)}\left(\mu_{\widetilde{A}_k}^{L} + \mu_{\widetilde{A}_k}^{U}\right)}{2}}{\sqrt{\sum_{j=1}^{J} \frac{\lambda^{(j)}\left(\mu_{\widetilde{A}_k}^{L\ 2} + \mu_{\widetilde{A}_k}^{U\ 2} + \nu_{\widetilde{A}_k}^{L\ 2} + \nu_{\widetilde{A}_k}^{U\ 2}\right)}{2}}} \tag{22}$$

3.3. Grade Evaluation with FCE

Using the weighted indicators from the IVIF-AHP method, FCE comprehensively considers all the indicators to arrive at the final status score for urban mobility. It may fully utilize people's experiences, resulting in more objective and genuine evaluation outcomes. Experts in many fields are involved in this portion of urban mobility assessment, which is a subjective process. Thus, FCE is a valuable technique for the solution of a variety of non-deterministic issues because it can fully represent people's experiences, thus making the evaluation results more objective and real. As a result, this method was altered to obtain an overall score for urban transportation.

Step 1: Establishment of the evaluation factor set.

Assuming that each evaluation layer has n evaluation indicators, it is recorded as follows:

$$U = \{u_1, u_2, \cdots, u_n\} \tag{23}$$

where n is the number of indicators in an evaluated layer and u_n is the original value of the indicator.

Step 2: Establishment of the rating set P.

The comprehensive performance evaluation result of urban mobility is quantified into m grades. The rating set is defined using Equation (24).

$$P = \{p_1, p_2, \cdots, p_m\} \tag{24}$$

Step 3: Construction of the fuzzy matrix Q.

The fuzzy matrix Q is defined as:

$$Q = \begin{bmatrix} q_{11} & q_{12} & \cdots & q_{1m} \\ q_{21} & q_{22} & \cdots & q_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ q_{n1} & q_{n2} & \cdots & q_{nm} \end{bmatrix} \tag{25}$$

where m is the number of grades and n is the number of indicators. Moreover, q_{n1}, q_{n2}, ... q_{nm} are the membership grade function values of each indicator obtained from the experts' grading scores.

Step 4: Calculation of the synthetic result vector Y.

The evaluation result vector Y of the evaluation indicator U_1 is calculated as:

$$Y = VQ = [v_1\ v_2\ \cdots\ v_n] \times \begin{bmatrix} q_{11} & q_{12} & \cdots & q_{1m} \\ q_{21} & q_{22} & \cdots & q_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ q_{n1} & q_{n2} & \cdots & q_{nm} \end{bmatrix} = [y_1\ y_2\ \cdots\ y_m] \tag{26}$$

where $v_1, v_2, \cdots, v_n(\sum_1^n v = 1)$ are the weights of each indicator in each evaluated layer, and $y_1, y_2, \cdots, y_m$ are the possibilities in each grade.

Step 5: Calculation of the evaluation result score.

The final evaluation score is calculated using Equation (27), and the evaluation of each criteria layer and factor layer can be obtained in the same way.

$$G = P \times Y^T = p_1 \times y_1 + p_2 \times y_2 + \cdots + p_m \times y_m \tag{27}$$

The procedural framework is presented in Figure 3.

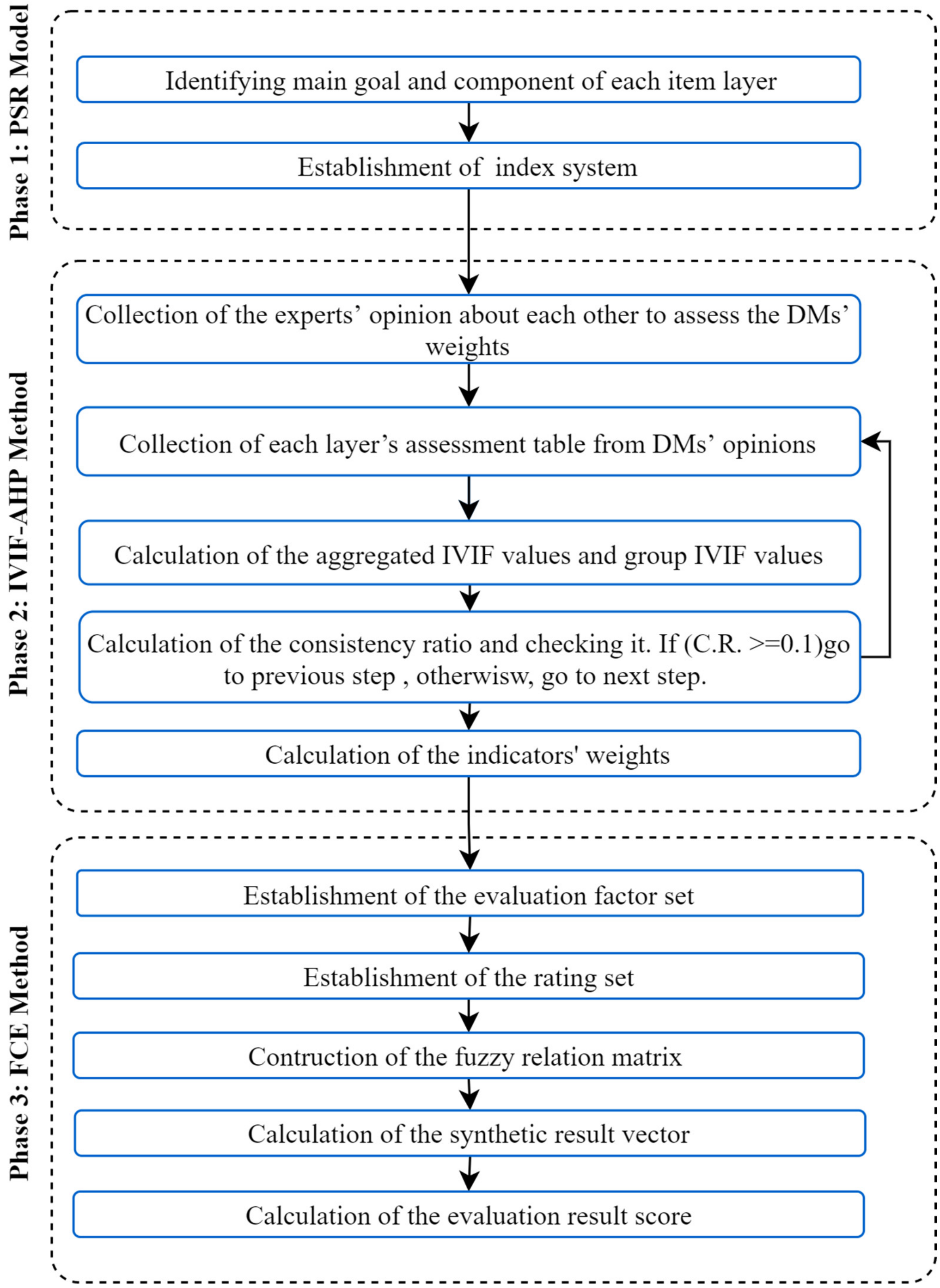

Figure 3. The steps of the proposed methodology.

4. Case Study

4.1. Case Background

Beijing is the capital of and second largest city in China. Since the late 1990s, Beijing's urban transportation planners and managers have faced significant challenges as a result of the city's fast economic growth and urbanization. In the past 20 years, the population of Beijing has increased from 13.633 million to 21.893 million [101,102]. In the same period, the number of private vehicles has increased by 4.99 million [103]. Additionally, the average commuting time of residents has increased to 56 mins due to the unreasonable urban structure [104].

From the supply side, Beijing's urban mobility system provides various travel options and is composed of public buses, urban rail transit, taxis, online car-hailing, private cars, and bicycles By the end of 2020, Beijing's road network totaled 22,264 km; the operational lengths of bus and urban rail transit lines, respectively, reached 28,418 km and 727 km; and the numbers of taxis and shared bikes, respectively, were 71,500 and 844,000. The enormous mobility system serves 36.19 million daily trips in the central urban area during weekdays [105]. Therefore, the operation condition and service performance of each component of the system have great impacts on the mobility environment and the quality of life of citizens and thus deserve full attention and systematic monitoring and evaluation.

To cope with the various pressures and improve the status of Beijing's urban mobility system, since 2004 a comprehensive mobility improvement plan has been issued by the Beijing government every year, including the promotion of the construction of the urban road network, the construction of bus and bicycle lanes, comprehensive pedestrian treatment, and the optimization of the bus line network [106].

Therefore, Beijing's urban mobility system itself provides a notable representation of the correlation of pressure, state, and response factors. In addition, with the acceleration of urbanization worldwide, similar problems are likely to be encountered in other cities. Based on the aforementioned reasons, Beijing serves as a good case study.

4.2. Implementation of the Proposed Model

The evaluation criteria were first identified and the hierarchical structure was built using the PSR model, which was introduced in Section 3.1. The hierarchical structure has 25 indicators that sufficiently reflect the statuses of the pressure, state, and response in the urban mobility system.

Experience, academic backgrounds, and knowledge of Beijing's urban mobility system were taken into consideration for the selection of DMs. Let DMs = {Expert 1, Expert 2, Expert 3, Expert 4, Expert 5} be the set of DMs. Expert 1 is a manager of a metro company that provides software and infrastructure services to the metro in Beijing. Expert 2 is a university professor in Beijing who is studying public transportation. Expert 3 is a researcher at a transportation research institute who is studying urban traffic economy. Expert 4 is a university professor in Beijing who is studying traffic safety and transportation policy. Finally, Expert 5 is the owner of a company that provides consulting services related to urban transportation in Beijing. Due to confidentiality and privacy issues, additional information about the DMs cannot be supplied. Each DM was evaluated by the other DMs using the linguistic terms (Table 3), as summarized in Table 6. To conduct aggregation, the assessments of each DM were transformed to aggregated IVIF values using Equations (11)–(14), and the DMs' weights (λ^j) were computed with Equation (15) using the aggregated IVIF values, as presented in Table 7.

Table 6. The DMs' judgments of each other.

Evaluated Object	Evaluators			
$Expert_1$	$Expert_2$ LQ	$Expert_3$ Q	$Expert_4$ Q	$Expert_5$ LQ
$Expert_2$	$Expert_1$ Q	$Expert_3$ VQ	$Expert_4$ Q	$Expert_5$ VQ
$Expert_3$	$Expert_1$ Q	$Expert_2$ LQ	$Expert_4$ Q	$Expert_5$ LQ
$Expert_4$	$Expert_1$ VQ	$Expert_2$ RQ	$Expert_3$ Q	$Expert_5$ RQ
$Expert_5$	$Expert_1$ Q	$Expert_2$ Q	$Expert_3$ Q	$Expert_4$ Q

Table 7. The IVIF values and the weight of each DM.

DM	$[\mu_{\tilde{A}}^{L}, \mu_{\tilde{A}}^{U}]$	$[\nu_{\tilde{A}}^{L}, \nu_{\tilde{A}}^{U}]$	$[\pi_{\tilde{A}}^{L}, \pi_{\tilde{A}}^{U}]$	λ^{j}
$Expert_1$	[0.600,0.665]	[0.122,0.187]	[0.148,0.278]	0.182
$Expert_2$	[0.900,1.000]	[0.000,0.000]	[0.000,0.100]	0.219
$Expert_3$	[0.600,0.665]	[0.122,0.187]	[0.148,0.278]	0.182
$Expert_4$	[0.800,1.000]	[0.000,0.000]	[0.000,0.200]	0.208
$Expert_5$	[0.800,0.850]	[0.050,0.100]	[0.050,0.150]	0.209

To calculate the weight of each indicator, taking the pressure criteria layer as an example, the DMs evaluated the indicators according to the linguistic scale shown in Table 4. Table 8 exhibits the linguistic term-based assessments made by each DM. The linguistic terms given in Table 8 were then transformed into aggregated IVIF values by Equations (16)–(19), and Table 9 reports the IVIF value of each DM and the corresponding group IVIF value for the pressure indicators. The calculation process of the IVIF values of the other layers was the same, and the results are reported in Table 10. Subsequently, the CR was computed by Equation (20). All layers were found to have CR values of less than 0.1, and therefore no modification was required. Finally, the local and global weights of the indicators in each layer were obtained by Equations (21) and (22), and the results are reported in Table 11.

Table 8. The DMs' judgments of the pressure indicators by the linguistic terms.

DM	$Expert_1$				$Expert_2$				$Expert_3$				$Expert_4$				$Expert_5$			
Indicator	I_1	I_2	I_3	I_4	I_1	I_2	I_3	I_4	I_1	I_2	I_3	I_4	I_1	I_2	I_3	I_4	I_1	I_2	I_3	I_4
I_1	EI				EI	SI	SI	MI	EI				EI		SI		EI		EVI	
I_2	SI	EI				EI	MI		SI	EI	SI	SI	MI	EI	MI		VSMI	EI	SMI	SI
I_3	MI	EI	EI				EI		MI		EI	MI			EI				EI	
I_4	SI	EI	SI	EI		EI	SI	EI	SI			EI	VSMI	SI	SI	EI	MI		SI	EI

Table 9. The aggregated IVIF values and group IVIF values of the pressure indicators.

Indicators of Pressure	$[\mu_{\tilde{A}}^{L}, \mu_{\tilde{A}}^{U}]$	$[\nu_{\tilde{A}}^{L}, \nu_{\tilde{A}}^{U}]$	$[\pi_{\tilde{A}}^{L}, \pi_{\tilde{A}}^{U}]$
	$Expert_1$		
I_1	[0.1122,0.3836]	[0.2376,0.6164]	[0.0000,0.6503]
I_2	[0.1835,0.4244]	[0.3290,0.5756]	[0.0000,0.4875]
I_3	[0.1865,0.3404]	[0.2100,0.6596]	[0.0000,0.6035]
I_4	[0.2012,0.3769]	[0.2189,0.6231]	[0.0000,0.5799]
	$Expert_2$		
I_1	[0.1720,0.4362]	[0.1039,0.5638]	[0.0000,0.7241]
I_2	[0.1797,0.4353]	[0.1723,0.5647]	[0.0000,0.6480]
I_3	[0.1334,0.4413]	[0.1774,0.5587]	[0.0000,0.6893]
I_4	[0.2185,0.4450]	[0.1738,0.5550]	[0.0000,0.6077]
	$Expert_3$		
I_1	[0.1122,0.3836]	[0.2376,0.6164]	[0.0000,0.6503]
I_2	[0.1504,0.4003]	[0.1777,0.5997]	[0.0000,0.6718]
I_3	[0.1294,0.3425]	[0.1461,0.6575]	[0.0000,0.7245]
I_4	[0.1229,0.3969]	[0.2123,0.6031]	[0.0000,0.6649]
	$Expert_4$		
I_1	[0.1417,0.4035]	[0.2253,0.5965]	[0.0000,0.6330]
I_2	[0.1471,0.3821]	[0.1099,0.6179]	[0.0000,0.7430[
I_3	[0.1277,0.4263]	[0.1920,0.5737]	[0.0000,0.6804]
I_4	[0.2677,0.5012]	[0.1414,0.4988]	[0.0000,0.5909]

Table 9. *Cont.*

Indicators of Pressure	$[\mu_{\tilde{A}}^{L},\mu_{\tilde{A}}^{U}]$	$[\nu_{\tilde{A}}^{L},\nu_{\tilde{A}}^{U}]$	$[\pi_{\tilde{A}}^{L},\pi_{\tilde{A}}^{U}]$
	Expert_5		
I_1	[0.1766,0.3731]	[0.2539,0.6247]	[0.0022,0.5695]
I_2	[0.3032,0.5212]	[0.1468,0.4788]	[0.0000,0.5500]
I_3	[0.1465,0.4086]	[0.2912,0.5885]	[0.0030,0.5623]
I_4	[0.1525,0.4051]	[0.1324,0.5949]	[0.0000,0.7151]
	Group IVIF value		
I_1	[0.1449,0.3971]	[0.2092,0.6025]	[0.0005,0.6460]
I_2	[0.1941,0.4338]	[0.1835,0.5662]	[0.0000,0.6224]
I_3	[0.1439,0.3950]	[0.2044,0.6044]	[0.0006,0.6517]
I_4	[0.1944,0.4272]	[0.1736,0.5728]	[0.0000,0.6320]

Table 10. The group IVIF values of each layer.

Element of Each Layer	$[\mu_{\tilde{A}}^{L},\mu_{\tilde{A}}^{U}]$	$[\nu_{\tilde{A}}^{L},\nu_{\tilde{A}}^{U}]$	$[\pi_{\tilde{A}}^{L},\pi_{\tilde{A}}^{U}]$
	Criteria layer		
C_1	[0.1116,0.2344]	[0.4880,0.7656]	[0.0000,0.4004]
C_2	[0.3460,0.4979]	[0.2568,0.5009]	[0.0012,0.3971]
C_3	[0.3902,0.4845]	[0.2261,0.5146]	[0.0009,0.3837]
	Factor layer		
F_1	[0.1725,0.3557]	[0.3181,0.6443]	[0.0000,0.5093]
F_2	[0.1504,0.3203]	[0.3006,0.6797]	[0.0000,0.5490]
F_3	[0.1477,0.2996]	[0.3288,0.7004]	[0.0000,0.5235]
	Indicator layer (C_1)		
I_1	[0.1449,0.3971]	[0.2092,0.6025]	[0.0005,0.6460]
I_2	[0.1941,0.4338]	[0.1835,0.5662]	[0.0000,0.6224]
I_3	[0.1439,0.3950]	[0.2044,0.6044]	[0.0006,0.6517]
I_4	[0.1944,0.4272]	[0.1736,0.5728]	[0.0000,0.6320]
	Indicator layer (C_2-F_1)		
I_5	[0.1755,0.5950]	[0.1141,0.4032]	[0.0018,0.7104]
I_6	[0.2036,0.5285]	[0.0482,0.4711]	[0.0004,0.7482]
I_7	[0.1875,0.5436]	[0.0428,0.4559]	[0.0005,0.7698]
I_8	[0.2114,0.5474]	[0.0559,0.4524]	[0.0002,0.7327]
I_9	[0.1739,0.5587]	[0.0568,0.4412]	[0.0001,0.7693]
I_{10}	[0.1973,0.5563]	[0.0650,0.4433]	[0.0004,0.7377]
	Indicator layer (C_2-F_2)		
I_{11}	[0.1852,0.4948]	[0.0867,0.5052]	[0.0000,0.7281]
I_{12}	[0.1846,0.5031]	[0.1011,0.4969]	[0.0000,0.7144]
I_{13}	[0.1720,0.4718]	[0.0720,0.5282]	[0.0000,0.7560]
I_{14}	[0.1588,0.4888]	[0.1210,0.5112]	[0.0000,0.7202]
I_{15}	[0.1602,0.4837]	[0.1414,0.5163]	[0.0000,0.6984]
	Indicator layer (C_2-F_3)		
I_{16}	[0.1794,0.4715]	[0.0871,0.5285]	[0.0000,0.7336]
I_{17}	[0.1942,0.4778]	[0.0802,0.5222]	[0.0000,0.7256]
I_{18}	[0.1579,0.4884]	[0.1058,0.5116]	[0.0000,0.7363]
I_{19}	[0.1604,0.4938]	[0.1055,0.5062]	[0.0000,0.7342]
I_{20}	[0.1400,0.5029]	[0.1256,0.4971]	[0.0000,0.7344]
	Indicator layer (C_3)		
I_{21}	[0.1603,0.4982]	[0.0988,0.5018]	[0.0000,0.7409]
I_{22}	[0.1908,0.4913]	[0.0951,0.5087]	[0.0000,0.7141]
I_{23}	[0.1674,0.4899]	[0.1026,0.5101]	[0.0000,0.7300]
I_{24}	[0.1543,0.4802]	[0.1064,0.5198]	[0.0000,0.7393]
I_{25}	[0.1495,0.4867]	[0.0820,0.5133]	[0.0000,0.7684]

Table 11. The weights used for the urban mobility assessment index.

Criteria Layer (Weight)	Factor Layer (Weight)	Indicator Layer	Weight	Global Weight
C_1: Pressure (0.1507)		I_1: The pressure of population growth	0.2318	0.0349
		I_2: The pressure of private vehicle ownership growth	0.2698	0.0407
		I_3: The pressure of urban area growth	0.2308	0.0348
		I_4: The pressure of an unreasonable urban structure	0.2674	0.0403
C_2: State (0.4196)	F_1: Public transport (0.3685)	I_5: Density level of public transport routes	0.1701	0.0263
		I_6: Bus travel speed during peak hours	0.1639	0.0253
		I_7: Social environment of giving preference to public transportation travel	0.1644	0.0254
		I_8: Punctuality of public transport	0.1687	0.0261
		I_9: Connection performance between urban transit and other modes	0.1647	0.0255
		I_{10}: Density level of urban public transportation stations	0.1681	0.0260
	F_2: Non-motorized travel (0.3272)	I_{11}: Social environment of giving preference to non-motorized travel	0.2059	0.0283
		I_{12}: Pedestrian walkway setting level	0.2077	0.0285
		I_{13}: Density level of the bicycle network	0.1959	0.0269
		I_{14}: Supply and demand matching performance of shared bikes	0.1964	0.0270
		I_{15}: The partition between motor vehicles and non-motorized traffic	0.1942	0.0267
	F_3: Personalized travel (0.3036)	I_{16}: Average travel speed of private vehicles during peak hours	0.1988	0.0253
		I_{17}: Congestion duration level of private vehicles on weekdays	0.2046	0.0261
		I_{18}: Supply capacity of parking spaces	0.1983	0.0253
		I_{19}: Convenience level of car rental	0.2007	0.0256
		I_{20}: Average response speed of taxis and online car-hailing	0.1975	0.0252
C_3: Response (0.4292)		I_{21}: Improvement of urban traffic management	0.2017	0.0866
		I_{22}: Improvement of urban transport policy and regulations	0.2070	0.0889
		I_{23}: Improvement of urban transport intelligence and informatization	0.2008	0.0862
		I_{24}: The policy of supporting clean energy and new-energy vehicles	0.1943	0.0834
		I_{25}: Improvement of regulating and monitoring the service of taxis and online car-hailing	0.1960	0.0841

To obtain the final score of Beijing's urban mobility system, the evaluation factor set was first established according to the index system. Taking the pressure as an example, the four indicators of pressure were recorded as $U_p = \{u_1, u_2, u_3, u_4\}$ by Equation (23). The rating set was then constructed via Equation (24) by dividing it into five grades, which were recorded as $P = \{\text{Grade I}, \text{Grade II}, \text{Grade III}, \text{Grade IV}, \text{ Grade V}\}$. Grade I means that the pressure has the least negative impact on the urban mobility system, the system state is in excellent condition, and the response measures are the most active and effective. In contrast, Grade V means that the pressure has the greatest negative impact, the system state is in the worst condition, and the response measures are the most passive and ineffective. The other grades reflect the corresponding intermediate values. The corresponding value of each grade is reported in Table 12.

Table 12. The grade ratings and scores.

Grade	I	II	III	IV	V
Interval value	[0.8,1]	[0.6,0.8]	[0.4,0.6]	[0.2,0.4]	[0,0.2]
Score	90	70	50	30	10

A multi-disciplinary team composed of 30 experts from the fields of transportation, urban and regional planning, environmental engineering, and economics was interviewed in this study. These experts were not only specialist evaluators, but also users of Beijing's urban mobility system. To obtain the fuzzy relationship matrix, 30 experts who lived in and were familiar with Beijing were engaged in the assessment study. They evaluated the current status of each indicator for Beijing's urban mobility, which was graded as I, II, III, IV, or V. The evaluation grade of each indicator is reported in Table 13. The global weight of each indicator was obtained by the IVIF-AHP method. Moreover, the vector result (0.0619, 0.3610, 0.3081, 0.1341, 0.1339) was obtained using Equation (26). Finally, the final score of the Beijing mobility system was obtained using Equation (27).

Table 13. The FCE results for the urban mobility assessment of Beijing.

Indicator	Grade
I_1. The pressure of population growth	V
I_2. The pressure of private vehicle ownership growth	V
I_3. The pressure of urban area growth	IV
I_4. The pressure of an unreasonable urban structure	V
I_5. Density level of public transport routes	II
I_6. Bus travel speed during peak hours	III
I_7. Social environment of giving preference to public transportation travel	II
I_8. Punctuality of public transport	III
I_9. Connection performance between urban transit and other modes	II
I_{10}. Density level of urban public transportation stations	II
I_{11}. Social environment of giving preference to non-motorized travel	III
I_{12}. Pedestrian walkway setting level	III
I_{13}. Density level of the bicycle network	III
I_{14}. Supply and demand matching performance of shared bikes	II
I_{15}. The partition between motor vehicles and non-motorized traffic	III
I_{16}. Average travel speed of private vehicles during peak hours	IV
I_{17}. Congestion duration level of private vehicles on weekdays	III
I_{18}. Supply capacity of parking spaces	III
I_{19}. Convenience level of car rental	III
I_{20}. Average response speed of taxis and online car-hailing	II
I_{21}. Improvement of urban traffic management	III
I_{22}. Improvement of urban transport policy and regulations	III
I_{23}. Improvement of urban transport intelligence and informatization	II
I_{24}.The policy of supporting clean energy and new-energy vehicles	II
I_{25}. Improvement of regulating and monitoring service of the taxis and online car-hailing	II

5. Results and Discussion

5.1. IVIF-AHP Weight for Each Indicator

As shown in Table 11, the weights of the pressure, state, and response criteria layers obtained by the IVIF-AHP method were, respectively, 0.1507, 0.4196, and 0.4292. According to additional interviews with the experts, compared with the other two criteria layers, despite the huge population and number of vehicles, an excessive urban area and unreasonable urban structure are important factors that cause a reduction in urban mobility service performance in megacities such as Beijing. Due to the dynamic balance between supply and demand, which is one of the essential basic characteristics of megacities, when the preceding negative pressure reaches a certain level, the negative effects of the rising pressure are mitigated and gradually stabilized. Moreover, an effective and efficient supply capacity, as well as active and effective response strategies, will become increasingly important for reliable and sustainable urban mobility.

Regarding the pressure criteria layer, the pressure of private vehicle ownership growth was found to have the highest global weight (0.0407), followed by the pressure of an unreasonable urban structure (0.0403), the pressure of population growth (0.0349), and the pressure of urban area growth (0.0348). As adjusting the urban structure is a huge and complex project, restricting the increase in private vehicles and encouraging people to travel by public transport are the key measures used for the reduction in the external pressure on urban mobility.

The weights of the 16 public transport, non-motorized travel, and personalized travel indicators in the state criteria layer were found to have lower global weight compared with indicators in the other two criteria layer. According to the Beijing Transport Institute [105], the proportions of the travel volume of public transport, non-motorized travel, and personalized travel are, respectively 26.6% (urban rail transit and buses account for 14.8% and 11.8%, respectively), 46.9% (walking and bicycling account for 31.4% and 15.5%, respectively), and 26.5%. Therefore, indicators of the pedestrian walkway setting level (0.0285) and the social environment of giving preference to non-motorized travel (0.0283) ranked first and second in the state criteria layer, respectively.

Regarding the response criteria layer, the improvement of urban transport policies and regulations was found to have the largest weight (0.0889), followed by the improvement of urban traffic management (0.0866), the improvement of urban transport intelligence and informatization (0.0862), the improvement of regulating and monitoring services of taxis and online car-hailing (0.0841), and the policy of supporting clean energy and new-energy vehicles (0.0834). All five indicators were found to have high weight values, indicating that the most significant way to improve urban mobility, particularly in megacities such as Beijing, is to promptly and effectively address and respond to potential problems. The efficacy of urban mobility enhancement, as one of the most significant management tasks of city government, is heavily dependent on the direction and strength of relevant policies.

5.2. FCE Assessment Result

The comprehensive score of Beijing's urban mobility system was found to be 51.608, which is in Grade III. Moreover, the pressure, state, and response assessment results were, respectively, 18.258 (Grade V), 52.679 (Grade III), and 62.336 (Grade II). Based on this study, it was found that, despite the fact that Beijing's urban mobility system is under pressure from a variety of sources, the general supply matching and development reaction ability are at a relatively decent level. The grade of each indicator is presented in Table 13 and Figure 4; 9 indicators were in Grade II, 11 indicators were in Grade III, 2 indicators were in Grade IV, 3 indicators were in Grade V, and no indicators were in Grade I.

Three-quarters of the pressure-layer indicators belong to Grade V, which means that Beijing's urban mobility system is still under a very large amount of pressure from the increase in the population and private vehicle ownership. According to the National Bureau of Statistics [102], Beijing's average annual population growth rate was 1.1% from 2010 to 2019. Although the growth rate was 2.7% lower than the rate from 2010 to 2010, as a megacity and the political center of China, the increase in the population of Beijing is inevitable, and the population density of the core area of the city is over 1.9 thousand persons/km^2. The unreasonable urban structure also has an obvious negative impact on Beijing's urban mobility system.

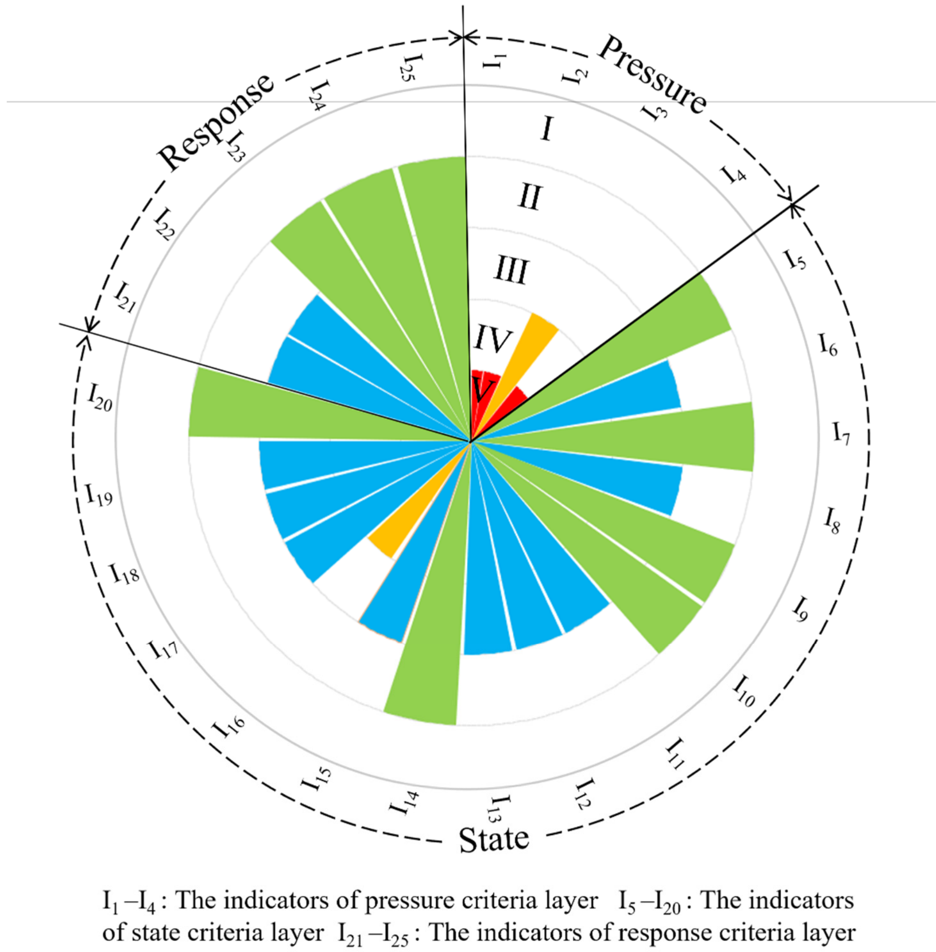

Figure 4. The FCE results for the urban mobility assessment of Beijing.

Regarding the public transport layer, four indicators were in Grade II, and the indicators of the bus travel speed during peak hours and the connection performance between urban transit and other modes were in Grade III. Given that public transportation will account for 56% of all travel by 2025 [107], the current policy direction of continual network optimization and the installation of high-occupancy vehicle (HOV) lanes to increase public transportation service levels is important.

Regarding the non-motorized traffic layer, except for the Grade II supply and demand matching performance of shared bikes, the remaining four indicators were all found to be in Grade III. Since 2015, Beijing's bicycle-sharing system has developed very quickly, and has had a good influence on the improvement of the satisfaction with non-motorized traffic. However, the overall travel environment, particularly the walking and cycling space, has led to concerns regarding travel safety and comfort, and therefore must still be addressed.

Regarding the personalized travel layer, the average travel speed of private vehicles during peak hours was found to have the lowest grade among all the state indicators. The experts believe that, despite the implementation of a public transportation priority policy, private vehicle travel speeds in Beijing are still being ignored, and greater attention is therefore needed to alleviate traffic congestion during peak hours. Furthermore, due to the continuous improvement of online car-hailing matching algorithms and a sufficient vehicle supply, the response speed indicator was found to be well scored in this study. Nevertheless, multiple experts pointed out that the inadequate parking facilities and car-sharing vehicles might be potential threats to the sustainable development of Beijing's mobility system in the future, and similar opinions regarding other cities in China have also been expressed in previous research [108].

Regarding the response criteria layer, the policy of supporting clean energy and new-energy vehicles, the improvement of urban transport intelligence and informatization, and the improvement of regulating and monitoring taxi and online car-hailing services received high scores from the experts. As discussed in previous research, the effective promotion of clean energy and new-energy vehicles is not only a technological choice, but also a political choice [109]. Beijing has been issuing policies to boost new-energy vehicles as its primary strategy for urban mobility development since 2014—e.g., new-energy vehicles—are not restricted by traffic control measures (policies to limit the number of cars on the road during a prescribed period), are allowed to use bus lanes, and are offered free parking. The average annual rate of the increase in new-energy vehicles from 2014 to 2020 was 132.7%, compared with 4% for private vehicles [105]. Moreover, the first pilot MaaS application in China was launched by the Beijing Transportation Commission and Amap company in 2019 [110]. Additionally, according to data from the Beijing Traffic Management Bureau [111], the crash death rate has been decreasing over the last four years. Nevertheless, Beijing must still focus on improving urban traffic management and urban transportation policies and regulations, such as by having a more positive and open attitude toward the development of emerging E-bike mobility [112].

6. Conclusions

A good urban mobility system has a positive influence on daily life and improves the satisfaction of citizens in a city. Thus, it is necessary to evaluate urban mobility with a new methodology. Based on the PSR model, 25 indicators that reflect the current status of the urban mobility system were utilized in this study, and a corresponding evaluation index system was put forward. Via the proposed method integrating both the IVIF-AHP and FCE methods, the indicator weights and assessment scores of urban mobility can be obtained. In contrast to other methods, the judgment made by the proposed method is more precise due to the use of fuzzy theory. The results of a case study conducted in Beijing revealed that the urban mobility of Beijing is under a substantial amount of pressure, including pressure from population growth, private vehicle ownership growth, and unreasonable urban structure. More efforts must be devoted to the control of traffic congestion in Beijing. This case study supported the validity and viability of the proposed method. Nevertheless, this study faced some limitations, as follows: (1) In terms of dealing with indicators, if the number of indicators is overly large, the approach may require a more complex process. (2) A sufficient number of experts with a professional background must be invited in the implementation process of the proposed method. This increases the difficulty of model implementation in complex mobility systems with various travel options. (3) Due to spatial constraints, various calculations and grading processes were not discussed in this publication.

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