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Coupling Coordination Relationships between Urban-industrial Land Use Efficiency and Accessibility of Highway Networks: Evidence from Beijing-Tianjin-Hebei Urban Agglomeration, China

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Abstract: The implementation of the Beijing, Tianjin, and Hebei coordinated development strategy has seriously increased the influence of land use and urban traffic. Thus, understanding the coordination between urban land and transportation systems is important for the efficient and sustainable development of cities, especially in this rapidly urbanizing era. Urban-industrial land and highway networks are, respectively, primary types of urban land and transportation systems, and have significant impacts on social and economic development. However, limited studies have been conducted to examine the relationships between urban-industrial land and highway networks. Therefore, this paper aims to examine the coupling coordination relationship between urban-industrial land use efficiency, and the accessibility of the highway networks of cities. Specifically, in the context of the Beijing-Tianjin-Hebei (BTH) urban agglomeration, the coupling coordination between urban-industrial land use efficiency and accessibility of the highway traffic network was empirically analyzed. The results show that: (i) The differences in urban-industrial land use efficiency in the BTH region are significant. Capital cities in the BTH urban agglomeration have higher economic, social, and comprehensive efficiency, while in industrial cities, the use of urban-industrial land should prioritize ecological and environmental issues. (ii) Because of its good geographical location Beijing has the best accessibility, with an accessibility index of 1.416, while Qinhuangdao had the lowest accessibility index of 0.039. (iii) In most BTH cities, the urban-industrial comprehensive land use level has fallen behind the highway network development level. The results of this study can provide references for the coordinated development of the BTH urban agglomeration.

Keywords: urban-industrial land; efficiency; highway networks; accessibility; coupling coordination relationship; Beijing-Tianjin-Hebei urban agglomeration

1. Introduction

In cities, land is at the root of urban development, relating to the coordinated development of economic, social, environmental, and other factors. With rapid urbanization and growth of the urban

population, urban land supply is under increasing pressure. The land resource supply has become an important factor restricting urban development [1,2]. For most cities around the world, urban sprawl is becoming the main way to ease urban land tensions. However, the side effects of urban sprawl, including cultivated land reduction, traffic congestion, and environmental pollution, have further limited urban development [3–5]. The most reasonable approach for urban sustainable development is to optimize urban spaces and improve land use efficiency (efficiency is usually defined as output in relation to input, and land use efficiency is used to calculate the Gross Domestic Product (GDP) per square meter [6,7]), in addition to making urban land more functional [8,9].

According to the *Code for Classification of Urban Land Use and Planning Standards of Development Land (GB 50137–2011)* [10], urban construction land (the generic name for residential land, public facilities land, industrial land, storage land, diplomatic land, road plaza land, municipal public facilities land, green space, and other special land) can be subdivided into multiple categories. Research on specific urban construction land prediction is increasing gradually. Nevertheless, a comprehensive study predicting the total urban construction land and specific urban construction land is yet to be carried out. Moreover, the research methods and content regarding specific urban construction land prediction need to be improved. Urban–industrial land is the main type of urban construction land [11,12], and is also the main space for urban non-agricultural activities [13]. China has experienced urban land expansion alongside rapid urbanization. There was 38.59 million hectares of construction land by the end of 2015, including 31.42 million hectares of urban-industrial land and rural residential area. Accounting for 37.4% of the total land supply in China, land supply in the eastern region has reached an annual increasing rate of 3.9%. There is an increasing pressure on urban land supply [14]. In order to adapt to the new normal of economic development, optimize the land supply structure, support new industry development, and ensure the rational and healthy development of industrial land, China has issued a series of policy documents on industrial structure optimization. In October 2015, the Chinese government put forward the development concept of “innovation, coordination, green development, opening up, and sharing,” clearly aiming to shape the new patterns of regional coordinated development. Beijing, Tianjin, and Hebei have been required to plan industrial land as a whole, and control sprawling of urban-industrial land [15]. It is of great significance to explore urban-industrial land efficiency.

Meanwhile, China has improved the status of highway traffic through a series of measures since 2003. The investment in highway and waterway infrastructure had reached 0.23 trillion dollars by the end of the year 2003. Meanwhile, highway mileage increased by 8260 km, and rural road mileage increased by 210,000 km [16]. Rapid development to manage highway traffic has effectively alleviated the tense situation of transportation in China. However, the planning and construction of the existing national highway network still faced some problems [17]. First, the coverage of the national highway network was not comprehensive [18]. More than 900 counties across the country did not have access to national highways, and 18 new cities with populations of more than 200,000, along with 29 administrative centers at the prefectural level, had not been connected to the national highways [19]. Second, the transportation capacity is insufficient. The traffic capacity of some highway channels is tight, and the traffic congestion is serious, which does not meet the needs of rapid traffic growth [20]. Third, the highway network efficiency is relatively low. The route of the national highway is discontinuous and incomplete, the links between the national highway and other modes of transportation are inadequate, and the network benefit and efficiency are difficult to bring into play [21]. Therefore, it is necessary to consider the role of the national highway in guiding regional spatial distribution, to optimize the network structure of highways in the eastern region, to strengthen the construction of links between the east and the west in the central region, to expand the coverage of the national highway in the western region, and to coordinate urban and rural development. Putting forward the concept of “accessibility”, which refers to the size of the interaction potential between two geographical nodes in the traffic network, Hansen (1959) proposed that it was not only related to the spatial and temporal barrier between two nodes, but also their quality and scale, and he

studied the relationship between urban land use change and accessibility by using the potential model. The potential model can be used to calculate the interaction potential between the regional nodes [22,23]. It is of great necessity to examine in more detail the accessibility of highway networks.

As one of the emerging economic agglomeration areas in eastern China, many cities in the Beijing–Tianjin–Hebei (BTH) urban agglomeration have faced problems, such as scattered layouts and low efficiency of urban-industrial land (their Gross Domestic Product per square meter of urban-industrial land is low) [24]. Since the implementation of the Beijing, Tianjin, and Hebei coordinated development strategy in 2014, the industrial transfer projects of Tianjin and Hebei have blossomed [25]. Tianjin has 15 industrial transfer projects, with a total planning area of 1030 km², of which only 36.8% (379 km²) was in line with the overall land use planning. Meanwhile, 11 cities and 170 counties in Hebei Province have more than 270 industrial transfer projects, with a total planning area of 19,500 km², exceeding the total area of Beijing (16,400 km²). The state-owned construction land supply of Beijing was 4100 ha in 2016, which was 12.2% lower than that in 2015. The industrial land sales of Tianjin and Hebei also declined from 2015 [26]. Hence, the dilemma between the blind expansion of undertaking industrial transfer projects and actual demand for land use was obvious. On the other hand, from the perspective of regional scale, passenger transportation in the BTH area was heavily dependent on highways, with railways accounting for less than 10% [27]. The public transit sharing rate in the center of big cities in the BTH urban agglomeration has been increasing over the past decades. In Beijing, where the public transit share rate was 50%, and the car share rate was 32% in 2015 [27]. Based on the above analysis, transportation integration and industrial upgrading were the priorities of coordinated development in the BTH urban agglomeration [28].

For the sustainable development of cities, it is essential to explore the relationship between land use and urban traffic (traffic in urban areas) from the perspective of spatial layout and traffic planning, and to analyze the coordination between them. According to the synergy theory between urban land use and urban traffic, with the continuous coordination development of these two systems, the relationship between traffic supply and demand could change and a matching mechanism of supply and demand would be formed [29]. Therefore, this paper aims to examine the coupling coordination relationship between urban–industrial land use efficiency and accessibility of highway networks of cities. In specific, in the context of the Beijing–Tianjin–Hebei (BTH) urban agglomeration, this paper is designed to: (1) examine urban-industrial land use efficiency of BTH cities; (2) estimate accessibility of highway networks of BTH cities; and (3) identify the coupling coordination relationship between urban–industrial land use efficiency and accessibility of highway networks.

2. Literature Review

The interaction between land use and transportation is a hot topic in the fields of geography, economics, and land use planning [30–35]. Due to the former being a result of urban development, while the latter is simultaneously an outcome and an important driver, the interaction between urban land use and transportation is also an interrelated issue in policy making [36–39]. There are two objects in the evolution of urban land use and transportation: one is housing and enterprise, and the other is government departments. The location of housing and enterprises determines the distribution of the population and employment, which constitutes the structure of urban land use. Meanwhile, urban land use structure affects traffic demand and road investment decisions by the government [40,41]. In recent years, more and more scholars have been trying to explore the relationship between land use and urban traffic from the perspective of spatial layout and traffic planning, and to analyze the coordination between them [42].

2.1. The Effects of Urban Land Use on Urban Traffic

Urban land use layout plays a decisive role in urban traffic patterns [43]. Many scholars have proposed that urban land use characteristics have a significant influence on traffic travel behavior [44]. For example, travel mode, travel distance, and travel distribution could be affected

by land development density, land use intensity, and land use mixing degree [45,46]. The social, economic, and ecological efficiency of urban land has formed a relatively mature evaluation system, and the evaluation objects are basically concentrated in urban construction land [47,48] and industrial land [49]. The previous research also shows that there are two problems with the evaluation methods of construction land use efficiency. (1) The relationship between the evaluation indicators and construction land use efficiency is not correlated closely enough, and the scientific principle of indicator selection is not reflected [50]. (2) The calculation of comprehensive efficiency is only a summary of the three aspects of social, economic, and ecological efficiency, and fails to take into account the relationship between various parts [51,52].

2.2. The Effects of Urban Traffic on Urban Land Use

The urban transportation network, in affecting the urban land use spatial form, land use intensity, land use structure, and land price, has promoted the evolution of the urban spatial pattern [53–55]. Land fragmentation caused by the road traffic (traffic on the road) network has shown a significant spatial correlation with the urban land use spatial form [56]. Meanwhile, attention to the traffic network, improving location accessibility, and the evolution of the regional land use form along the route could lead to the formation of new land development intensive areas, and promote the development of the urban multi-center spatial structure [57,58]. The urban traffic network has shown a strong spatial attraction effect on land development along its route, and the intensity of land use in the surrounding areas of the traffic trunk line shows the law of distance attenuation [59]. The influence of the urban road traffic network on the land use structure is mainly manifested by the spatial attraction and spatial differentiation effect of traffic lines on urban land evolution [60]. The relevant studies have revealed the differential effects of different types of traffic corridors, such as light rail, trunk roads and expressways, on the spatial distribution of residential, commercial, industrial, and other land in cities [61].

The research methods of spatial accessibility evaluation mainly include location accessibility, effectiveness accessibility, and temporal-spatial accessibility [62,63]. The methods of accessibility evaluation reflect the different research objects: highway [64], expressway [65], subway [66], freight transport [67], and so forth. Research methods include the distance accessibility model, weighted average travel time model, time accessibility model, and potential model. The distance accessibility model, weighted average travel time model, and time accessibility model involve the accessibility evaluation of the space–time barrier, without analysis of the effect of the main nodal city on the surrounding nodal cities in an agglomeration area. The interrelationship between cities is not only related to the level of their own infrastructure, but also to the level of social and economic development, and the scale of cities in other node cities [68]. Therefore, more and more attention has been paid to the study of urban accessibility by adding social–economic effects, especially when using the weighted average travel time model. The weighted average travel time model can be used to measure the time between a node city and each economic center, through the influence of city size and development level on accessibility.

2.3. The Interaction between Urban Land Use and Urban Traffic

Based on accessibility theory and traffic supply and demand equilibrium theory, scholars have explored the relationship between urban land use and urban traffic. According to accessibility theory, due to the inhomogeneous distribution of transportation facilities, the difference of accessibility in different regions directly affects the travel decisions of residents and investment decisions of developers, thereby affecting land use and development [69,70]. According to traffic supply and demand equilibrium theory, land use is at the root of urban traffic demand, while the urban transportation system determines the traffic supply [71]. With the continuous development of the two systems, the relationship between traffic supply and demand could change, and a matching mechanism of supply and demand would be formed [72].

In recent years, scholars have tried to evaluate the coordination of urban land use and traffic based on various theoretical models (Table 1). The coordination of urban land use and traffic has been evaluated in terms of the fuzzy- analytic hierarchy process (AHP) multilayer evaluation model [73], data envelopment analysis model [74], and coupling coordination model [75]. We found that, first, land use indicators applied fuzzy- analytic hierarchy process (AHP) multilayer evaluation model focused on residential land area etc. while urban traffic indicators focused on road land area, etc. Second, land use indicators applied a data envelopment analysis model focused on average population density, etc. while urban traffic indicators focused on bus passenger capacity, etc. Based on different models, the land use and urban traffic indicators that have been adopted are diverse. Moreover, land use indicators applied coupling coordination model focused on land use density, etc., while urban traffic indicators focused on length of road network, etc. In addition to this, land use and public transportation could form an effects and feedback (Coupling Coordination) relationship [76]. Aiming at examining the coupling coordination between urban–industrial land use efficiency and accessibility of the highway traffic network, the coupling coordination model is appropriate to reveal the coupling coordination relationships between urban–industrial land use efficiency and accessibility of highway networks.

Table 1. The evaluation index system of urban land use and urban traffic coordination.

Coordination Evaluation Model	Land Use Indicators	Urban Traffic Indicators	References
FUZZY-AHP (Analytic Hierarchy Process) multilayer evaluation model	Residential land area, population density and employment density, land use layout	Road land area, public transport ratio during rush hour, vehicle ownership	[73]
Data envelopment analysis (DEA) model	Average population density, area of land for transport, proportion of employment and resident population	Bus passenger capacity, bus share rate, transit mileage, rail transit mileage, travel distance per person	[74]
Coupling coordination model	Land use density, land use scale, land use layout	Length of road network, length of rail transit operation, number of means of transport	[75]

3. Data and Materials

3.1. Study Area

The BTH urban agglomeration, covering a surface area of 217,158 km², is an important core area of northern China, including two municipalities directly under the Central Government of Beijing and Tianjin, and 11 prefecture-level cities of Hebei Province (including Shijiazhuang, Tangshan, Qinhuangdao, Handan, Xingtai, Baoding, Zhangjiakou, Chengde, Cangzhou, Langfang, and Hengshui) (Figure 1). In 2015, the resident population of the BTH urban agglomeration was 110 million, of which 69.573 million lived in cities and towns, and the urbanization rate reached 62.5%. The GDP of the region was 1.02 trillion dollars, and the proportion of the output value of primary industry, secondary industry, and tertiary industry was 3.68:40.67:54.67 [77]. There were significant differences in economic development, industry enterprise development, and road traffic construction in the cities of the BTH urban agglomeration (Table 2).

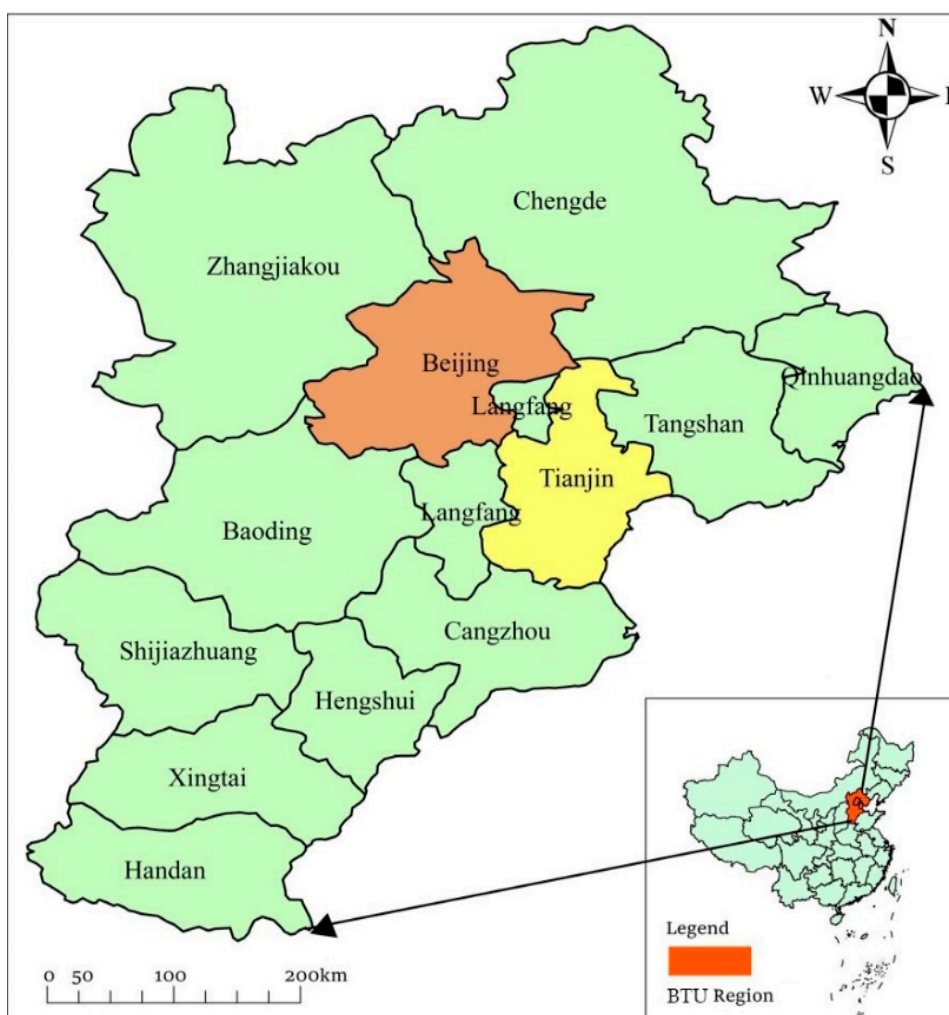


Figure 1. The map of the BTH (Beijing–Tianjin–Hebei) urban agglomeration.

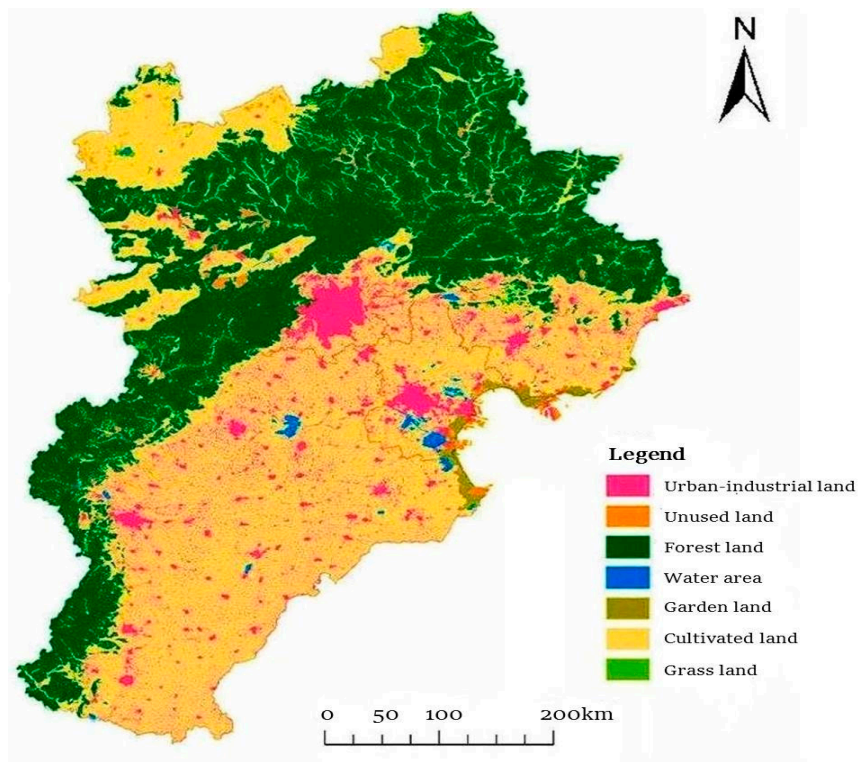
Table 2. Basic information for cities in the BTH (Beijing–Tianjin–Hebei) urban agglomeration.

City	Urban-Industrial Land/(km ²)	Area of City Paved Roads (ha)	Number of Industrial Enterprises	Composition of Gross Regional Product (%)		
				Primary	Secondary	Tertiary
Beijing	1747.33	10029	3548	0.61	19.74	79.7
Tianjin	1974.67	14019	5525	1.26	46.58	52.2
Shijiazhuang	586.00	5366	2752	9.09	45.08	45.8
Tangshan	1452.00	3098	1595	9.32	55.13	35.6
Qinhuangdao	244.00	2137	395	14.21	35.59	50.2
Handan	454.00	3161	1378	12.81	47.16	40.0
Xingtai	354.00	1519	1309	15.62	44.97	39.4
Baoding	586.00	3878	1665	11.78	50.02	38.2
Zhangjiakou	456.67	1375	564	17.87	40.01	42.1
Chengde	289.33	734	549	17.34	46.84	35.8
Cangzhou	858.67	968	2380	9.62	49.58	40.8
Langfang	363.33	937	1255	8.33	44.56	47.1
Hengshui	253.33	742	1234	13.84	46.15	40.0

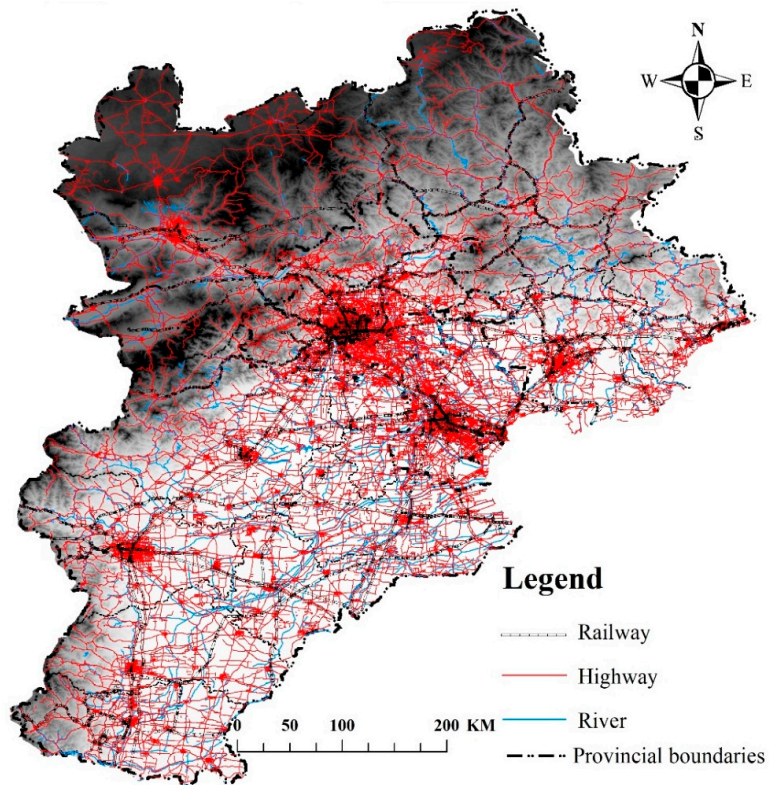
3.2. Data Collection

Urban–industrial land use data were collected from the national land utilization conveyance data in 2015 (<http://www.gscloud.cn/>). According to the overall land use plan of Beijing, Tianjin,

and Hebei, there were significant differences in the total amount of urban–industrial land in different cities in the BTH urban agglomeration in 2015 (Figure 2a).



(a)



(b)

Figure 2. (a) Land use map of the (Beijing-Tianjin-Hebei) (BTH) urban agglomeration in 2015; (b) highway networks of the BTH urban agglomeration in 2015.

Statistical data related to socio-economic conditions were collected from the Beijing Statistical Yearbook 2016 [78], Tianjin Statistical Yearbook 2016 [79], Hebei Statistical Yearbook 2016 [80], and China Statistical Yearbook for the Regional Economy 2016 [81]. We collected the spatial data (from the year of 2015) of the BTH urban agglomeration, including expressways, urban expressways, national highways, the local road networks, and administrative boundary, from the Openstreetmap Database (<https://www.openstreetmap.org/>). The highway network data set was established by using the Network Analysis Module in ArcGIS 10.2 (Figure 2b). According to the design speed of the Highway Engineering Technique Standards (JTG B01-2003) [82], to calculate travel time between the discretionary nodes of two cities, the average speed of various types of highways was defined: expressway 100 km/h, urban expressway 80 km/h, national highway 60 km/h, and local road network 40 km/h [82]. Data for the Digital Elevation Model (DEM) was collected from Geospatial Data Cloud (<http://www.gscloud.cn/>).

4. Establishment of the Coupling Coordination Model

4.1. Coupling Coordination Model

Specifically, to quantify the relationships, it is essential to calculate the coupling degree, coordination degree, and coupling coordination degree in coupling coordination [83].

4.1.1. Coupling Degree

The coupling degree literally means the degree of interaction relationships between two subsystems. It is often adopted to quantify the synergistic effect. The coupling degree model can be expressed as follows:

$$C = 2 \left[\frac{U_1 \times U_2}{(U_1 + U_2) \times (U_1 + U_2)} \right]^{\frac{1}{k}} \quad (1)$$

where C denotes the coupling degree, and k represents the adjustment coefficient and is the number of subsystems, normally set as 2. U_1 and U_2 stand for the performance levels of the two subsystems being examined, and the closer the value of U_1 or U_2 is to 1, the better the performance of the two subsystems [84]. The value of the coupling coordination degree is always between 0 and 1. When C is closer to 0, there will be a greater gap between the two subsystems, while a higher C value represents a higher coupling degree [85]. The coordination status can be divided into four types, namely low coupling ($0 < C \leq 0.3$, meaning the two subsystems have a minimal correlation), antagonism stage ($0.3 < C \leq 0.5$, meaning the two subsystems compete with each other), running-in stage ($0.5 < C \leq 0.8$, meaning the coupling of the two systems is benign), and highly coupling stage ($0.8 < C < 1$, meaning that the two systems have a strong correlation) [86].

4.1.2. Coordination Degree

As well as the coupling degree, it is essential to consider the coordination degree, which reflects the influences of the performance levels of the two subsystems on, or the contributions of the performance levels, to the coupling coordination degree [87]. The coordination degree can be expressed as follows:

$$T = \sum_{m=1}^n \beta_m U_m \quad (2)$$

where T_j represents the coordination degree, as well as the development level of the system. It can reflect the extent to which the indicators contribute to the degree of coupling and coordination of the system [85]. β_m represents the undetermined coefficient. Based on previous research [88], we defined that the contribution of urban-industrial land use efficiency and highway network accessibility to the whole system are the same. For example, urban-industrial land and the highway network are mutually improved, but neither are the individual driving factor to each other, so that $\beta_m = 0.5$ when $n = 2$.

4.1.3. Coupling Coordination Degree

Although the coupling degree can indicate the interaction relationship between two subsystems, it is hard to exhibit to what extent the actual development can interact [89]. Therefore, previous studies have recommended the inclusion of the coupling coordination degree, which is expressed as [85,87–89]:

$$D = \sqrt{C \times T} \quad (3)$$

where D represents the coupling coordination degree, and the value belongs to $[0,1]$. The coupling coordination degree, reflecting the degree of coupling and coordination of the subsystems during their interaction, is a positive measurement parameter. Based on previous research, we divided the coupling coordination degree into ten levels, as shown in Table 3 [85,87].

Table 3. Levels and corresponding criteria of the coupling coordination degree.

Coupling Coordination Type	Value	Coupling Coordination Level
Low coupling coordination	$0.00 < D \leq 0.09$	Extreme imbalance
	$0.10 \leq D \leq 0.19$	Serious imbalance
	$0.20 \leq D \leq 0.29$	Moderate imbalance
	$0.30 \leq D \leq 0.39$	Mild imbalance
Moderate coupling coordination	$0.40 \leq D \leq 0.49$	Imbalance
	$0.50 \leq D \leq 0.59$	Coordinate
Good coupling coordination	$0.60 \leq D \leq 0.69$	Basic coordinate
	$0.70 \leq D \leq 0.79$	Moderate coordinate
High quality coupling coordination	$0.80 \leq D \leq 0.89$	Good coordinate
	$0.90 \leq D < 1.00$	High quality coordinate

4.2. Urban-Industrial Land Use Efficiency Evaluation System Design

Urban–industrial land use efficiency refers to the sum of social, economic, and ecological efficiencies brought to the city through the reasonable arrangement, utilization, and optimization of urban–industrial land in space and time [14]. Urban–industrial land use efficiency evaluation, which is the estimation of urban–industrial land structure and function, should not only reflect the characteristics of urban–industrial land use, but also reflect the function and output of urban–industrial land [29]. This paper evaluated urban–industrial land use efficiency from three aspects: economic efficiency, social efficiency, and ecological efficiency. Economic efficiency reflects the relationship between input and output of land use. Social efficiency reflects the social bearing function, considering urban–industrial land has effectively supported population agglomeration and public infrastructure construction. Ecological efficiency is used to measure the impact of urban–industrial land on the ecological environment.

4.2.1. Data Processing and Weight Determination

In data processing, each indicator was converted by using the extremum method [89]. The calculation processes are expressed in Equations (4) and (5).

Positive indicator:

$$x = \frac{[x_{ij} - \min(x_j)]}{[\max(x_j) - \min(x_j)]} \quad (4)$$

Negative indicator:

$$x = \frac{[\max(x_j) - x_{ij}]}{[\max(x_j) - \min(x_j)]} \quad (5)$$

where x is the value of indicator x_{ij} processed by the extremum method; x_{ij} is the actual value of indicator i in the year j ; $\max(x_j)$ is the maximum actual value of indicator i in the year j ; and $\min(x_j)$ is the minimum actual value of indicator i in the year j .

For weight determination, the coefficient of variation method is used to determine the weight of each indicator [85]. Determination of the mean value of each indicator's eigenvalues uses

$$\bar{x}_j = \frac{1}{n} \sum_{i=1}^n x_{ij} \quad (i = 1, 2, \dots, n; j = 1, 2, \dots, m) \quad (6)$$

where x_{ij} represents the eigenvalue of the evaluation object i and the evaluation indicator j ; and \bar{x}_j represents the average of the eigenvalues for item j of all evaluation objects.

Standard deviation determination of the characteristic value of each evaluation indicator uses:

$$S_j = \sqrt{\frac{1}{n} \sum_{i=1}^n (x_{ij} - \bar{x}_j)^2} \quad (7)$$

where S_j represents the standard deviation of evaluation indicator j .

Determination of variation coefficient for eigenvalues of each evaluation indicator uses:

$$V_j = S_j / \bar{x}_j \quad (8)$$

where V_j represents the variation coefficient for eigenvalues of each evaluation indicator.

Determination of each evaluation indicator's weight uses:

$$\omega_j = V_j / \sum_{j=1}^n V_j \quad (9)$$

where ω_j represents weight evaluation indicator j .

4.2.2. Urban-Industrial Land Use Efficiency Evaluation

We used a comprehensive evaluation method to evaluate urban-industrial land use efficiency. The calculation method is given in Equations (10) and (11), as follows:

$$E_i = \sum_{n=1}^j W_{ij} \times x'_{ij} \times 100\% \quad (10)$$

where E_i represents the single efficiency, and W_{ij} represents the weight of secondary indicators.

$$E_{SUM} = \sum_{n=1}^3 W_j \times E_i \times 100\% \quad (11)$$

where E_{SUM} represents comprehensive efficiency. W_j represents the weight of primary indicators.

4.2.3. Evaluation Indicators

Urban-industrial land is the main component of urban land. The evaluation indicator selection of urban-industrial land use efficiency should be based on the content of urban land use evaluation, and according to the particularity of urban-industrial land, the evaluation indicators of urban land use should be adjusted appropriately. Based on the land use efficiency evaluation system and land intensive use evaluation system, we selected a range of urban-industrial land use efficiency evaluation indicators (Table 4).

Table 4. Urban–industrial land use efficiency evaluation system.

Primary Indicators	Subsystem Weight	Secondary Indicators	Index Type	Entropy Weight
Economic efficiency (U_1)	0.4586	Added value of the second and third industries (14.77 million dollars/km ²) (U_{11})	+	0.0245
		Average revenue (14.77 million dollars/km ²) (U_{12})	+	0.2578
		Average total retail sales of consumer goods (14.77 million dollars/km ²) (U_{13})	+	0.0629
		Return on fixed assets (%) (U_{14})	+	0.1134
Social efficiency (U_2)	0.3655	Per capita area of urban-industrial land (m ² /people) (U_{21})	−	0.0186
		Number of employees in the second and third industries (10000 people/km ²) (U_{22})	+	0.1438
		Per capita disposable income of urban residents (dollars) (U_{23})	+	0.0211
		Number of beds per health institution per 1000 population (U_{24})	+	0.1764
		Road area per capita (m ² /person) (U_{25})	+	0.0057
Ecological efficiency (U_3)	0.1758	Green coverage rate of built area (%) (U_{31})	+	0.001
		Green area rate of built area (%) (U_{32})	+	0.0013
		Energy consumption per unit of industrial output (t/dollars) (U_{33})	−	0.1052
		Treatment capacity of industrial wastewater (t/km ²) (U_{34})	+	0.0002
		Treatment capacity of industrial solid waste (t/km ²) (U_{35})	+	0.0681

4.3. Accessibility of Highway Networks Evaluation System Design

The accessibility evaluation method proposed in a previous study [21] was used and improved to evaluate the highway network system (U_2).

4.3.1. Regional Accessibility Evaluation Method

Various accessibility measurement methods have been employed to calculate different research objects, such as highways, high-speed railways, subways, and so forth. This paper calculated the time from a node city to the economic center by using the weighted average travel time model, as well as the influence of urban scale and development level on accessibility. However, the weighted average travel time model did not consider the influence of distance decay, and the length of the distance between the node cities played little role in calculating accessibility. For that reason, studies on accessibility of the node spatial interaction by using the potential model have become more and more dominant. Potential, which refers to the force between objects—for instance, the force of j on i A_{ij} is equal to M_j/C_{ij} , where M_j refers to the activity scale of node j —is often calculated by a city's social and economic development indicators, such as the gross domestic product. C_{ij} refers to the travel impedance factor (distance). This paper used A_i to show the sum of the forces generated by an object distributed on objects distributed in space to node i , and the potential model was calculated as follows:

$$A_i = \sum_{j=1}^n \frac{M_j}{C_{ij}^a} \quad (12)$$

where a denotes the node cities' travel friction coefficient, which reflects the influence degree of a spatial and temporal barrier on the accessibility relation of any two node cities.

4.3.2. Improved Accessibility Evaluation Method

Due to M_j in the method of reachability measurement not reflecting the typicality and systematisms of indicators selecting, we improved the method by using the city center function intensity index. The city center function intensity index can reflect the scale of the city and its economic development level [21]. At first, this paper calculated the function intensity index of every node city's social and economic data. Secondly, this paper evaluated the scale of every city, and its economic development level. The city center function intensity index can be calculated as follows:

$$K_x = \frac{X_i}{(\sum_{i=1}^n X_i)/n} \quad (13)$$

where X_i refers to the social-economic indicator of city i (the GDP).

This paper used the resident population (P_i), proportion of urban population (U_i), and economically active population (E_i) to reflect city i 's scale and urbanization level. Then, this paper calculated the central function intensity indices of the three indicators separately, and denoted them as K_{Gi} , K_{Ti} and K_{Vi} . To reflect city i 's infrastructural and economic level, this paper selected GDP (G_i), the percentage of second industry (S_i), the percentage of tertiary industry (T_i), and the total investment in fixed assets (V_i) as corresponding indices, and denoted them as K_{Gi} , K_{Ti} and K_{Vi} . Due to a lack of research references regarding indicator selection, this paper had to set identical weights of the center function index of each indicator to calculate their arithmetic mean value, to obtain every node city's scale and economic level index (M_j), as follows:

$$M_j = \frac{K_{Pj} + K_{Uj} + K_{Ej} + K_{Gj} + K_{Sj} + K_{Tj} + K_{Vj}}{n} \quad (14)$$

Improved potential model:

$$A_i = \sum_{j=1}^n \frac{K_{Pi} + K_{Ui} + K_{Ei} + K_{Gi} + K_{Si} + K_{Ti} + K_{Vi}}{nC_{ij}^a} \quad (15)$$

5. Results and Discussion

5.1. Urban–Industrial Land Use Efficiency

We firstly assessed the urban–industrial land use efficiency, including the economic efficiency, social efficiency, ecological efficiency, and comprehensive efficiency, of all cities in the BTH urban agglomeration, as shown in Figure 3.

Overall, there were significant differences among economic, social, and ecological efficiencies, found through comparing the efficiency values in Figure 3a–c. The economic efficiency of the urban-industrial land ranged between 0.026 and 0.453, and the social efficiency of the urban–industrial land of all cities in the BTH urban agglomeration ranged between 0.026 and 0.343. In comparison, the ecological efficiency of urban–industrial land only ranged between 0.006 and 0.070, far less than the values of economic and social efficiency. These results are consistent with the long-term city development pattern in China, in which various local governments have given priority to economic and social development, while the ecological environment has been neglected. Meanwhile, the low value of ecological efficiency also reflects that the urban industrial–land in the BTH urban agglomeration is currently under great ecological pressure, which should be urgently alleviated in future development.

Meanwhile, there were large differences among the economic, social, and ecological efficiencies of different cities. Obviously, Beijing and Tianjin outperformed other cities in all economic and social aspects, with economic efficiency values of 0.453 (Beijing) and 0.233 (Tianjin), and social efficiency values of 0.343 (Beijing) and 0.219 (Tianjin). These values were far higher than those of 11 cities in Hebei Province. Moreover, Beijing had the highest ecological efficiency value of 0.07, at least two

times the values of all other cities, including Tianjin city. For ecological efficiency, it is observed that the values of Qinhuangdao and Chengde were much higher, which reflects the preservation of the ecological environment of these areas during development by local governments. However, other cities demonstrated low values. This means Beijing and Tianjin still had the highest urban–industrial land efficiency, while other cities had low urban–industrial land efficiency. The apparent differences in economic, social, and ecological efficiency have further resulted in large gaps in comprehensive efficiency (Figure 3d).

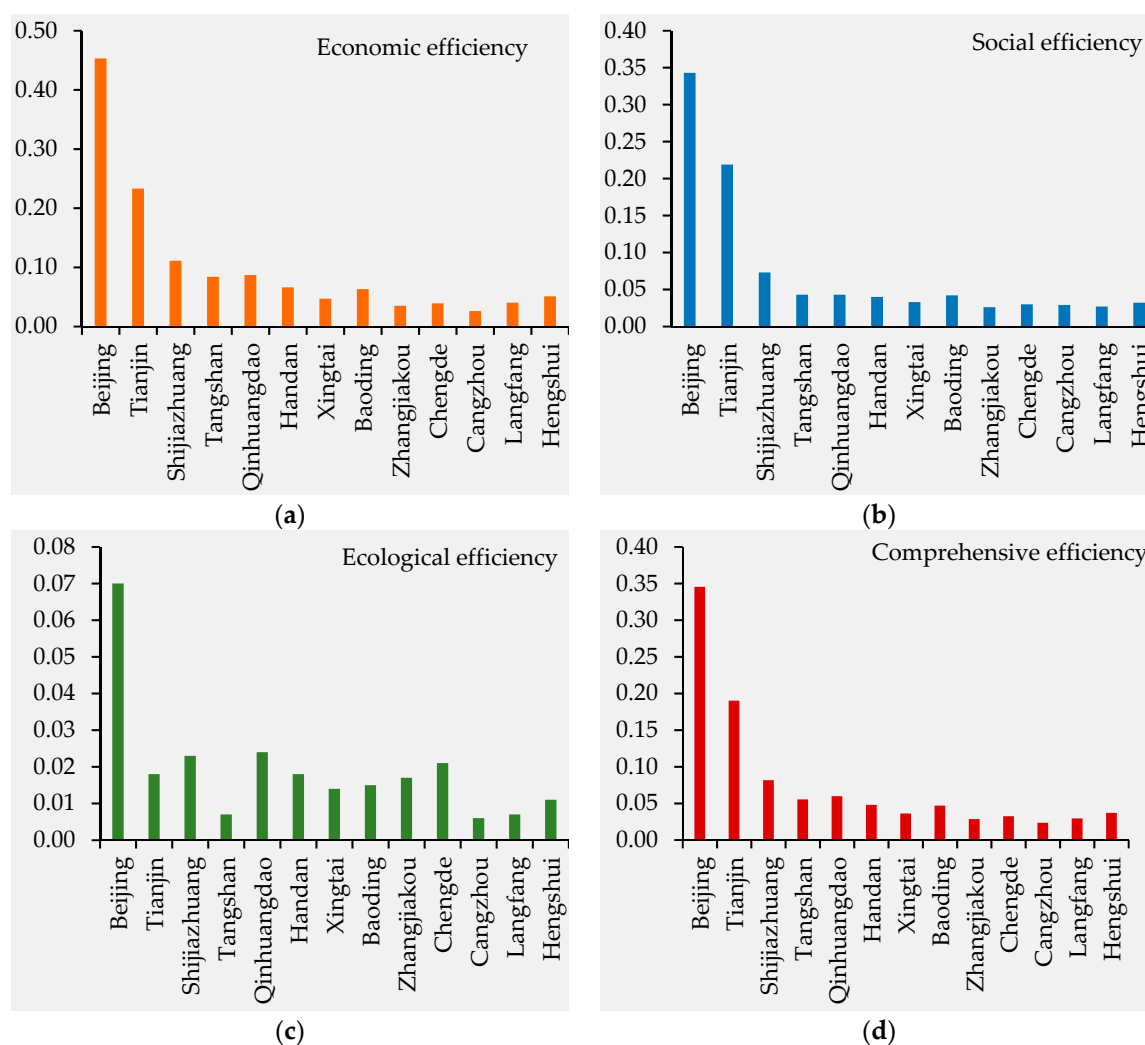


Figure 3. Evaluation results of urban-industrial land use efficiency in the (Beijing–Tianjin–Hebei) BTH urban agglomeration. (a) Economic efficiency, (b) social efficiency, (c) ecological efficiency, and (d) comprehensive efficiency.

To understand the causes of the current patterns of urban–industrial land use, we explored the economic, social, and ecological efficiencies based on the components listed in Table 4. Undoubtedly, with advanced manufacturing and modern service industries as pillar industries and intensive land use levels, Beijing, Tianjin, Shijiazhuang, Qinhuangdao, Tangshan, and other cities had high levels of urban–industrial land use economic efficiencies. Beijing, Tianjin, Baoding, and Langfang showed high levels of urban–industrial land use social efficiencies. Beijing, Qinhuangdao, Shijiazhuang, and Chengde showed high levels of urban–industrial land use ecological efficiencies. Nevertheless, due to the particularity of industrial industries, the ecological environment in Baoding, Tangshan, Langfang, and other cities was faced with difficulties in governance. Furthermore, as central cities in

the BTH urban agglomeration, Beijing, Tianjin, and Shijiazhuang had high levels of urban–industrial land use comprehensive efficiency.

Overall, in the current era, the advocated pattern of the BTH urban agglomeration is that Beijing should upgrade its industrial pattern through transferring primary and secondary industry to Tianjin and cities in Hebei Province [4]. This policy is aimed at conserving land resources, promoting Beijing’s industry sustainability, and driving the economic and social development of Tianjin and Hebei’s cities. However, enterprises have only set up subsidiary companies in Tianjin and Hebei’s cities, without practical operation of these new companies [25]. This, on the one hand, has pulled down the ecological efficiency of Tianjin and Hebei’s cities, and on the other hand, has significantly deteriorated the economic and social efficiency of Tianjin and Hebei’s cities without real economic and social output. However, the current industry upgradation policy of the BTH urban agglomeration has gone astray because of the imbalance of urban–industrial land use. More critically, the current implementation of the industry upgradation policy has not only failed to conserve land, but has also severely aggravated land resource waste [90].

5.2. Accessibility of Highway Networks

Urban economic development affects the spatial direction of traffic flow [91]. By giving economic weight to the shortest travel time, the weighted average travel time based on time distance can weaken the spatial blocking effect of geographical location on accessibility, and strengthen the relationship between economic development and accessibility. Moreover, urban accessibility can be measured through urban scale and economy [92]. Therefore, measuring the urban scale and economy grade of the cities in the BTH urban agglomeration, as well as comparing their size and classifying their grades, is the basic premise for understanding the accessibility of each city. Each node city’s urban scale and economy grade M_j was calculated using the ArcGIS 10.2 Natural Breaks Classification method, and we divided the value of M_j into five classes (Table 5). Table 5 presents the urban scale and economy grades of all cities in the BTH urban agglomeration [93].

Table 5. Urban scale and economy grades of cities in the (Beijing–Tianjin–Hebei) (BTH) urban agglomeration.

Grade	Economic Development Characteristics	Cities
1	Economic radiation center	Beijing, Tianjin
2	Advanced economic agglomeration	Shijiazhuang, Tangshan
3	Intermediate economic agglomeration	Baoding, Handan
4	Primary economic agglomeration	Cangzhou, Langfang, Qinhuangdao, Xingtai, Zhangjiakou
5	Economically backward areas	Chengde, Hengshui

As shown in Table 4, there were five types of urban scale and economy grades in the BTH urban agglomeration, where Beijing and Tianjin were the two cities listed as the economic radiation center. Among all the cities in Hebei Province, Shijiazhuang and Tangshan were the two characterized as having advanced economic agglomeration, with relatively higher urban accessibility, followed by Baoding and Handan. Cangzhou, Langfang, Qinhuangdao, Xingtai, and Zhangjiakou were cities with the characteristics of primary economic agglomeration, and Chengde and Hengshui were the economically backward areas with the lowest urban accessibility.

The highest urban scale and economy grades, which were 3.192 and 2.648 respectively, were shared by Beijing and Tianjin. Following Beijing and Tianjin, the score of the urban scale and economy grades of Shijiazhuang and Tangshan, which were important bases for the manufacturing and emerging industries in the BTH region, were 1.117 and 1.002, respectively. From the regional distribution, as the top cities of economic development in the BTH region, Beijing and Tianjin shared an urban scale and economy grade of 1, and were located in the core area of the BTH region. Cities that shared the urban scale and economy grade of 2, which included Tangshan in the coastal areas and Shijiazhuang in the west wing, were not only distributed widely, but also showed obvious regional characteristics. Regional differences indicated that Tangshan and Shijiazhuang have been becoming economic centers

of the east and west wings of the BTH region. It was noteworthy that the grade of Cangzhou's urban scale and economy was only 4. However, compared with Handan, the resident population and economically active population of Cangzhou was far less than that in Handan, although their gross domestic product and percentage of tertiary industry were roughly the same. Therefore, the low population size has become the restrictive factor of Cangzhou's urban scale and economy. Baoding and Handan, whose urban scale and economy grade was 3, were located in the south area of the BTH region.

The cities that shared an urban scale and economy grade of 4, which included Cangzhou, Langfang, Qinhuangdao, Xingtai, and Zhangjiakou, were mainly located in the northwest, northeast, and southeast areas of the BTH region. Cities that shared an urban scale and economy grade of 5, which included Chengde and Hengshui, were mainly located in the north and south areas of the BTH region. Those cities sharing low urban scale and economy grades were almost always located in mountainous areas, and their location conditions are very poor. With an urban scale and economy grade of 5, Hengshui is a barrier to urban agglomeration in the south area, and to core urban agglomeration in the BTH region. Such a regional difference showed that the radiometric force from the core urban agglomeration in the BTH region to Xingtai and Handan in the south area was relatively weak. Generally speaking, spatial differences in urban scale and economy grade characterization revealed that the farther a city is away from the center of regional economy, the weaker the city's external force and economic radiation ability. That is, the urban space and economic radiation ability between cities was distance diminishing.

We further used the city's scale and economic level index (M_j) to reflect the weight index, and measured the accessibility index (A_i) of each node city in BTH urban agglomeration, by using the improved potential model, as shown in Figure 4.

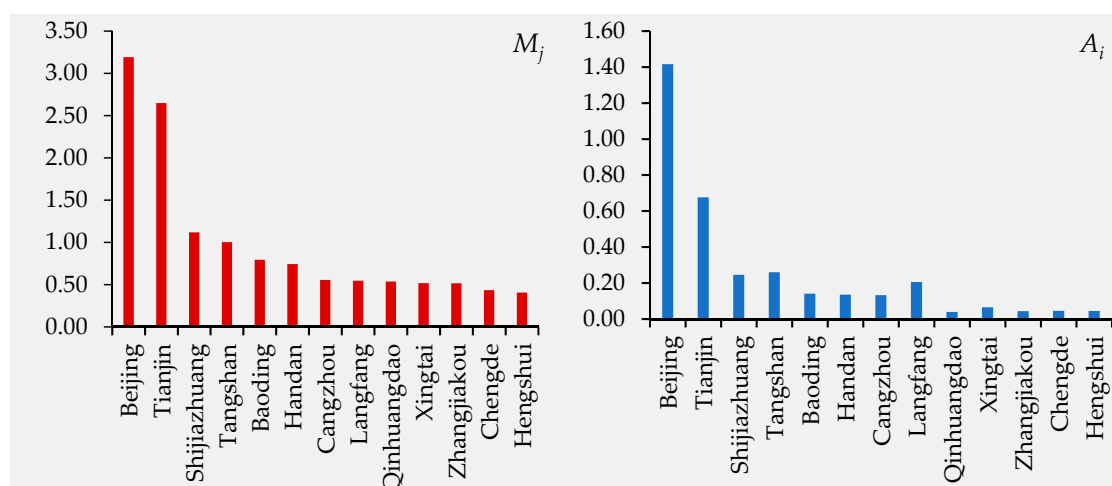


Figure 4. Accessibility index of highway networks in the BTH (Beijing–Tianjin–Hebei) urban agglomeration.

With a good geographical location and good economic conditions of the surrounding cities, the A_i of Beijing reached 1.416—optimal in the BTH region. However, with an urban scale and economy grade of 4, the A_i of Qinhuangdao ($A_i = 0.039$) was the lowest in the BTH region. This indicates that the greater the distance between the city and the regional economic center, the more obvious the influence of geographical location on the level of accessibility. In addition, the M_j and A_i of Baoding and Langfang were heterogeneous. The A_i of Langfang, with an urban scale and economy grade of 4, was higher than that of Baoding, with an urban scale and economy grade of 3. That the A_i of Baoding was slightly higher than that of Handan indicated that the spatial function and economic influence of the surrounding cities of Langfang were larger than that of the surrounding cities of Baoding.

Based on the above analysis, using the ArcGIS 10.2 Natural Neighbor Interpolation method, we obtained the regional accessibility (A_i) spatial pattern and characteristics in the BTH region (Figure 5). From the perspective of geographical location, the A_i of the whole BTH urban agglomeration was relatively high. The accessibility spatial distribution showed an expanding trend from Beijing to peripheral cities; namely, the farther a city was away from the center of regional economy, the weaker the A_i of the city. The geographical location conditions and the city's urban scale and economy grade influenced accessibility of the city. The results indicate that the greater the distance between the city and the regional economic center, the more obvious the influence of geographical location on the level of accessibility [93].

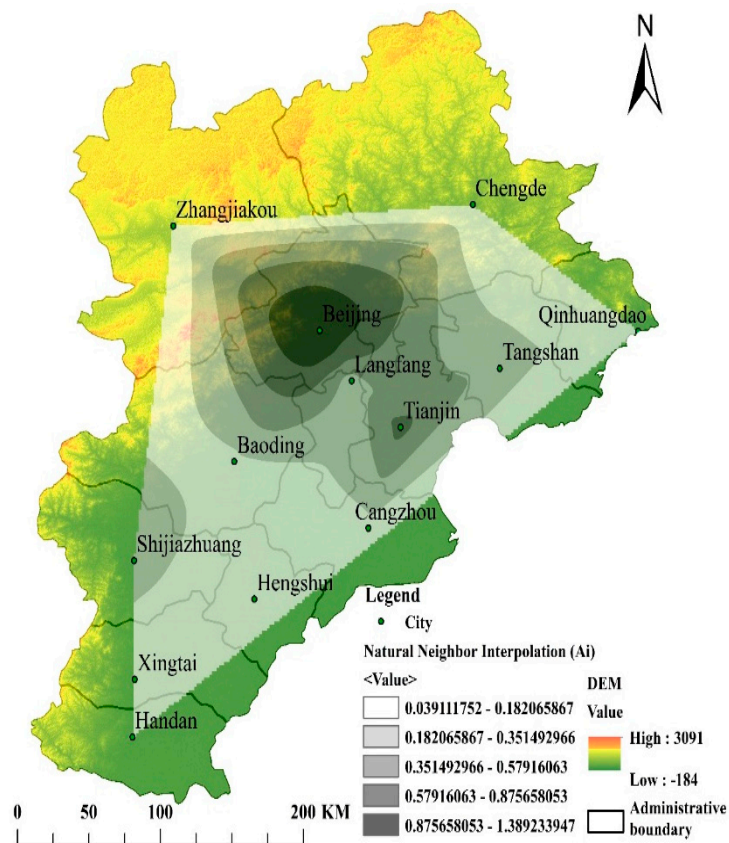


Figure 5. Regional accessibility (A_i) spatial pattern and characteristics in the BTH (Beijing-Tianjin-Hebei) urban agglomeration.

5.3. Coupling Coordination Relationship between the Urban-Industrial Land Use Efficiency System and Accessibility of Highway Networks System

Table 5 exhibits the coupling and coordination types between the urban-industrial comprehensive land use efficiency and accessibility of the highway network. Overall, the coupling coordination relationship showed a good coupling degree in Beijing, Tianjin, Qinhuangdao, Langfang, and Cangzhou. However, the coordination degree of these cities was relatively low. The degree of coupling coordination distinguishes between the benign and the destructive effects of the coupling action. The coordination degree was better than the coupling degree, which indicated that the urban-industrial land use efficiency system and accessibility of highway networks system were not mutually improved, and remained in hysteresis state.

According to the coupling and coordination states between the urban-industrial comprehensive land use efficiency (U_1) and accessibility of the highway network (U_2), we divided the hysteresis statuses of these two systems into three levels: (1) $U_1 > U_2$, urban-industrial land comprehensive efficiency (U_1) hysteresis; (2) $U_1 < U_2$, accessibility of the highway network (U_2); and (3) $U_1 = U_2$,

synchronous development (Table 6). The urban–industrial comprehensive land use level generally lagged behind the highway network development level in cities of the BTH urban agglomeration, except in Tangshan.

Table 6. Coupling and coordination types between the urban-industrial comprehensive land use efficiency and accessibility of the highway network.

City	Coupling and Coordination Types between U_1 and U_2				Hysteresis Status
	C	Coupling Status	D	Coupling Coordination Level	
Beijing	0.5314	Running-in stage	0.3597	Mild imbalance	U_1
Tianjin	0.5063	Running-in stage	0.2554	Moderate imbalance	U_1
Shijiazhuang	0.4764	Antagonism stage	0.1590	Serious imbalance	U_1
Qinhuangdao	0.5415	Running-in stage	0.1525	Serious imbalance	U_1
Tangshan	0.2562	Low coupling	0.0872	Extreme imbalance	U_2
Handan	0.4648	Antagonism stage	0.1196	Serious imbalance	U_1
Baoding	0.4755	Antagonism stage	0.1203	Serious imbalance	U_1
Hengshui	0.3254	Antagonism stage	0.0821	Extreme imbalance	U_1
Xingtai	0.3894	Antagonism stage	0.0910	Serious imbalance	U_1
Chengde	0.3478	Antagonism stage	0.0803	Extreme imbalance	U_1
Langfang	0.6189	Running-in stage	0.1243	Serious imbalance	U_1
Zhangjiakou	0.3610	Antagonism stage	0.0770	Extreme imbalance	U_1
Cangzhou	0.5846	Running-in stage	0.1037	Serious imbalance	U_1

In this study, the urban–industrial land use efficiency could affect urban functions, such as the urban ecological environment and accessibility of the urban highway network [94]. It also has implications for policy making in the fields of geography, economics, and land use planning [95]. This is because urban–industrial land, as a carrier for industries, is the link between enterprise and urban land. In cities, the land use pattern is always a result of urban development, while the transportation pattern can be a simultaneous outcome—and moreover an important driver—to urban development. In particular, enterprise and the local government are two objects which determine the evolution of urban land use and transportation. Both geographical location and operation of enterprises determine the distribution of the population and employment, which further constitutes the structure of urban land use in practice. Meanwhile, land use structure affects traffic demand and road investment decisions by the government.

The traffic network, through improving location accessibility and promoting the evolution of the regional land use pattern along its route, can lead to the formation of new land intensive areas and promote the development of a polycentric urban spatial structure [26]. As evidenced in this study, the urban traffic network has a strong spatial attraction effect on land development along the route, and the intensity of land use in the surrounding areas of the traffic trunk line follows the law of distance attenuation. The influence of the urban road traffic network on land use structure is mainly manifested by the spatial attraction and spatial differentiation effect of traffic lines on urban land evolution. The interrelationship between cities is not only related to the level of their own infrastructure, but also to the level of social and economic development, and the scale of cities in other node cities.

However, according to the national land utilization conveyance data from 2015, several problems have occurred in many cities of the BTH urban agglomeration, such as scattered layout, irrational structure, and low utilization efficiency of urban-industrial land. The central government has indicated that the BTH urban agglomeration should adhere to the new development concept of innovation, coordination, and green, orderly unblocked non-capital functions of Beijing, and promote the integrating development of industry with the implementation of the BTH region coordinated development strategy [96]. However, in the process of industrial transfer, a number of industrial parks, such as industrial compounds, demonstration areas, and industrial agglomeration areas, have been established and left over in the BTH urban agglomeration. Saving and intensifying industrial land

use in those cities has not been successful, and the low level of repeated construction causes low efficiency and extensive waste of industrial land. Therefore, saving and intensifying urban-industrial land use should be the main focus of coordinated development in the BTH urban agglomeration. With the serious situation of low urban-industrial land use efficiency, we suggest that the BTH urban agglomeration should tap the potential of urban land in stock. Beijing should strictly control the scale and development intensity of construction land and promote the city's functioning; Tianjin needs to reasonably control the scale of the central urban area and enhance the comprehensive carrying capacity; and Hebei should strengthen the industrial docking and coordination, and leave enough industrial land space to undertake the industrial base.

6. Research Implications and Limitations

6.1. Research Implications

The core of the coordinated development of the BTH urban agglomeration is to move labor-intensive and resource-dependent industries away from Beijing in an orderly manner, and to optimize urban layout and spatial structure and build a transportation network system in the BTH urban agglomeration.

In respect to urban land use, the Chinese government has implemented several measures in land use planning. For example, construction land has been strictly controlled; urban land use efficiency requires improvement; and urban-industrial land requires evaluation and re-use [96]. Nevertheless, evaluation of urban-industrial land use in BTH urban agglomeration is rarely understood. Urban-industrial land use efficiency evaluation in this paper can therefore provide a quantitative analysis for policy maker, and the results of urban-industrial land use efficiency in BTH urban agglomeration can provide a supplement for government specific land use planning.

In the respect of urban transport network, integrated transportation construction for the coordinated development of the BTH urban agglomeration has also been proposed [97]. The Chinese government have endeavored to build a multi-node transportation network in BTH urban agglomeration to relieve traffic pressure. However, there is currently no scientific prediction for the current status of the transportation network. The results of accessibility of highway networks evaluation in BTH urban agglomeration can also provide a supplement for government specific transport planning.

Last but not least, the Chinese government have been attempting to find a new path for coordinated development of BTH agglomeration in terms of spatial planning, transportation integration, and industrial upgrading. However, the specific functions of government departments are still limited to their respective functions [96–98]. For example, government departments between land use planning and transportation cannot cooperate with each other. Our work can provide inspirations for the unified planning of government departments between land use planning and transportation.

6.2. Research Limitations

There are some limitations to this study. First, based on the requirements of industrial adjustment, manufacturing industry agglomeration emerged in Hebei Province of the BTH urban agglomeration [90]. Thus, the concentration of industrial activities has not been considered. In future studies, we will consider the distinction between the cities of the BTH urban agglomeration and the concentration of industrial activities or highways. Second, the core of the coordinated development of the BTH urban agglomeration is to move labor-intensive and resource-dependent industries away from Beijing in an orderly manner, and to integrate transportation, ecological protection, and industrial upgrading in the BTH urban agglomeration. Future research can establish multiple composite systems covering urban-industrial land, the socio-economic industrial structure, the ecological environment, and transportation networks, making research results more comprehensive.

7. Conclusions

In this paper, an urban–industrial land use efficiency evaluation system was established, and the economic, social, ecological, and comprehensive efficiency of urban–industrial land of the cities in the BTH urban agglomeration were evaluated. The accessibility of the highway network in the BTH urban agglomeration was analyzed by using an improved accessibility evaluation method. We established a coupling coordination model to identify the relationship between urban–industrial land use efficiency and accessibility of the highway networks of cities in the BTH urban agglomeration. The results show that urban–industrial land use efficiency of cities in the BTH urban agglomeration showed significant differences, with central cities in the BTH urban agglomeration showing a high level of urban–industrial land use efficiency. Beijing had the best accessibility, and Qinhuangdao had the lowest accessibility within their geographical locations. The urban–industrial land use efficiency system and accessibility of the highway networks system were not mutually improved, and remained in hysteresis status. The urban–industrial comprehensive land use level generally fell behind the highway network development level in cities of the BTH urban agglomeration, except Tangshan.

Most of the existing research in this area focuses on the coupling and coordination relationship between industrial structures and industrial land use efficiency. For the BTH urban agglomeration, most studies have focused on the analysis of the coupling and coordination relationship of specific industries, such as manufacturing and productive services, the coupling and coordination relationship between industrial agglomeration and the ecological environment, and the coupling and coordination relationship between transportation and the regional economy. However, the three key areas of traffic integration, ecological environmental protection, and industrial upgrading and transfer are important to the coordinated development of the BTH urban agglomeration, and have been largely neglected. This paper examines the coupling and coordination relationship between urban–industrial land use efficiency and accessibility of highway networks, and addresses the gap in the existing literature. An improved accessibility evaluation method, which can enrich the accuracy of the accessibility method, is used to explore the accessibility of highway networks of cities in the BTH urban agglomeration.

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