Research on the Optimization of Air Route Networks in the Yangtze River Delta and Beijing-Tianjin-Hebei Urban Agglomerations from the Perspective of Spatial Interaction Intensity

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ABSTRACT

Scientific measurement of the spatial interaction intensity between the Yangtze River Delta and Beijing-Tianjin-Hebei urban agglomerations is an important basis for optimizing the design of air route networks in the Yangtze River Delta region. This paper constructs a modified gravity model based on air distance and measures the spatial interaction intensity between the two urban agglomerations using data from 2015 to 2019. Our findings show that the spatial interaction intensity between the Yangtze River Delta urban agglomeration as well as its cities and the Beijing-Tianjin-Hebei urban agglomeration presents a characteristic of "vertically steady increase and horizontal polarization", while the spatial interaction intensity between international aviation hubs, regional aviation hubs, and non-hub cluster cities of the two urban agglomerations is characterized by "vertically steady increase and horizontally gradient decline". Therefore, in the future, the Yangtze River Delta region should focus on consolidating the air transport links between Shanghai and Beijing, and significantly increase the frequency of air routes between hubs such as Nanjing, Hefei, Hangzhou, and Beijing, Tianjin, and Shijiazhuang. This will promote the coordinated "trunk and branch linkage" between hub and non-hub cluster airports and achieve differentiated and coordinated development among airports in the Yangtze River Delta.

Keywords: Air route networks, Spatial interaction intensity, World-class urban agglomeration, Modified gravity model.

I. Introduction

With the accelerated pace of urbanization in China, research on the coordinated development of world-class urban agglomerations and airport clusters has attracted widespread attention0. As a crucial engine for China's economic development, the Yangtze River Delta cluster is one of the regions with the highest degree of openness and strongest innovation capability in China 錯誤! 找

不到參照來源。. Thus, constructing a well-structured and functionally complete airport cluster in the Yangtze River Delta is a key support for building a higher-level urban agglomeration in the Yangtze River Delta region0, because airports play an increasingly important role in perfecting the comprehensive transportation hub system and promoting regional economic development. They can drive the development of a city[4], fully meet the diverse functional needs of world-class city clusters, provide strong support for their high-quality economic development, and become a key channel for China to integrate into the global economy 錯誤！找不到參照來源。. Meanwhile, world-class urban agglomerations may promote the development of world-class airport clusters due to continuously growing demands for air transportation, and they are complementary and mutually beneficial0.

Studies show that the Beijing-Tianjin-Hebei city cluster, with its significant strategic position, serves as an important driving force for China's high-quality economic development[7], shoulders the important task of China's participation in global competition and supporting and leading economic and social development0.The Beijing-Tianjin-Hebei airport cluster, as an important infrastructure, directly serves the functional positioning and development requirements of the Beijing-Tianjin-Hebei city clusters0. Connectivity directly reflects the quality of route network0. Improving the connectivity of air routes between the Yangtze River Delta and the Beijing-Tianjin-Hebei region is essential for fully leveraging the Yangtze River Delta and the Beijing-Tianjin-Hebei region as engines for high-quality economic development, and it is a crucial measure to support the high-level development of the new development pattern. Therefore, scientifically designing the air route network between the Yangtze River Delta and the Beijing-Tianjin-Hebei region has become an urgent practical issue for enhancing the coordinated and differentiated development of airports in the Yangtze River Delta0.

Existing literature shows that some scholars used gravitational models to examine the spatial interaction intensity between regions based on the characteristics of different transportation modes as a way to further optimize the transportation network design. Wang et al. (2014) used the gravitational model to measure the impact of high-speed railroads on the intensity of urban spatial interaction0. Tang and Zhang (2018) measured the spatial interaction intensity among 11 cities in Jiangxi province from the perspective of railroad transportation using the gravitational model, which provides a basis for steadily promoting the development of regional integration0. Li (2020) used the theory of spatial interaction model to analyze the impact of transportation network infrastructure construction on cities[14]. Ren et al. (2020) used an improved gravitational model to study the influencing factors of spatial interactions within cities[15]. Some scholars found that high-speed railroads promote regional economic integration and reduce regional economic disparities[16], which in turn affects the spatial pattern of city scale[17]. Bruinsma and Rietveld (1993) analyzed the impact of urban agglomerations based on the changes of roads, railroads, and airways by using the accessibility index[18]. Freestone and Baker (2011)[19] emphasized the significance of airports as both a product and a facilitator of globalization. They proposed that by adopting spatial planning models, airports should be synchronized with master plans and broader urban strategic plans. Measuring the spatial interaction intensity between regions under high-speed railroads, ordinary railroads and other patterns of transportation by means of the gravity model provides a new research idea and direction for measuring the spatial interaction intensity by using the modified gravity model so as to optimize the route network.

As major air transportation hubs, the Yangtze River Delta and Beijing-Tianjin-Hebei City Cluster have seldom utilized the enhanced gravity model, which is based on the comparative

advantages of air transportation, to investigate the spatial interaction strength between them, leaving a noticeable research gap. Therefore, this paper constructs a modified gravity model based on air transportation characteristics and uses data from 39 cities in the Yangtze River Delta and Beijing-Tianjin-Hebei urban agglomerations from 2015 to 2019 to measure the intensity of spatial interactions between the two city clusters. The aim is to optimize the connectivity of air routes within the Yangtze River Delta urban agglomeration, strengthen spatial interaction intensity between them, and provide reference for leveraging the support role of internal circulation patterns0.

2. Research Design

2.1 Research Subject and Data Sources

According to policy documents such as the "Development Plan for the Yangtze River Delta City Cluster" and the "Outline of the Plan for Coordinated Development of the Beijing-Tianjin-Hebei Region," this paper covers a total of 39 cities① in the above two urban agglomerations0. The Yangtze River Delta urban agglomeration consists of 26 cities such as Shanghai, with 1 international aviation hub city, 4 regional aviation hub cities, and 21 non-hub cluster cities), while the Beijing-Tianjin-Hebei urban agglomeration consists of 13 cities such as Beijing, with 1 international aviation hub city, 2 regional aviation hub cities, and 10 non-hub cluster cities. Meanwhile, due to the sudden impact of the COVID-19 pandemic in 2020 on the development of the air transportation industry, this paper takes the period from 2015 to 2019 as the time span. In addition, the data related to the gross domestic product (GDP) and total population at the end of the year for each city are sourced from the "China Statistical Yearbook", "China City Statistical Yearbook" and other relevant publications.

2.2 Research Model

The gravity model is commonly used to describe the intensity of spatial interactions, reflecting to some extent the level of economic connections between regions0. For this reason, this paper uses a distance-based modified gravity model in combination with the characteristics of air transportation operations to measure the intensity of spatial interactions between the "Yangtze River Delta-Beijing-Tianjin-Hebei" city clusters, as shown in formula (1) below:

$$L_{ij} = \frac{\sqrt{P_i * GDP_i} * \sqrt{P_j * GDP_j}}{D_{ij} * D_{ij}} \qquad (1)$$

Lij denotes the relationship between city i (i=1,2,...26) in the Yangtze River Delta urban agglomeration and city j (j=1,2,...13) in the Beijing-Tianjin-Hebei city cluster. where Pi and Pj respectively denote the total population of cities i and j at the end of the year (unit: 10,000 people), and GDPi and GDPj respectively denote the gross domestic product (GDP) of cities i and j (unit: ten thousand billion RMB).

In addition, Dij denotes the air distance between cities i and j (in km). If there are direct flights between cities i and j, the air distance can be directly obtained through the Great Circle Mapper. If there are no flights between two cities, the air distance is calculated by converting the ground transportation time from one city to the nearest city with flights (data obtained through Gaode Map) using the average flight speed of a Boeing 737 as the conversion standard.

Furthermore, to calculate the total intensity of spatial interactions between the cities in the Yangtze River Delta urban agglomeration and the cities in the Beijing-Tianjin-Hebei city cluster, this paper constructs formula (2) as follows:

$$L = \sum_{i\ j=1}^{n} L_{ij} \quad (2)$$

Where L denotes the total intensity of spatial interaction between city i in the Yangtze River Delta urban agglomeration and city j in the Beijing-Tianjin-Hebei city cluster, where n denotes the number of sample cities in the Beijing-Tianjin-Hebei city cluster, and the larger the value of L, the more significant the economic position between cities and the urban agglomeration based on air transportation.

3. Analysis of the Empirical Results

3.1 Empirical results of the spatial interaction intensity between the yangtze river delta and beijing-tianjin-hebei city clusters

Table 1 and Figure 1 show the empirical results of the spatial interaction intensity between the Yangtze River Delta urban agglomeration as well as cities within it and the Beijing-Tianjin-Hebei city cluster. It can be seen that the spatial interaction intensity between the Yangtze River Delta and Beijing-Tianjin-Hebe urban agglomerations is characterized by "vertically steady increase and horizontal polarization."

Table 1. Results of spatial interaction intensity between the Yangtze River Delta urban agglomeration as well as cities within it and the Beijing-Tianjin-Hebei urban agglomeration from 2015 to 2019

Year / City	2015	2016	2017	2018	2019	Five-year average	Year / City	2015	2016	2017	2018	2019	Five-year average
Shanghai	112.96	125.66	111.57	142.24	153.53	129.19	Anqing	7.53	7.63	4.19	9.15	10.62	7.82
Hefei	53.40	59.50	44.69	70.50	77.73	61.16	Jiaxing	5.04	6.44	2.84	7.41	7.82	5.91
Nan Jing	47.59	52.49	51.47	62.49	65.61	55.93	Zhenjiang	4.87	5.39	3.31	5.84	6.04	5.09
Hangzhou	39.00	48.79	43.89	58.90	63.48	50.81	Wuhu	4.28	4.75	3.43	5.52	5.82	4.76
Yancheng	37.45	41.46	31.17	57.44	57.88	45.08	Chuzhou	3.61	4.00	1.86	4.71	6.00	4.03
Nantong	31.21	40.87	24.43	47.78	50.00	38.85	Chizhou	3.56	3.91	2.90	4.49	4.91	3.95
Wuxi	28.23	29.74	21.97	35.58	36.13	30.33	Jinhua	3.30	3.23	1.41	4.43	4.69	3.41
Yangzhou	23.48	26.11	24.72	36.25	37.15	29.54	Zhoushan	2.86	3.21	4.26	3.51	3.56	3.48
Ningbo	23.87	26.30	20.44	31.03	32.79	26.88	Maanshan	3.00	3.32	2.30	3.93	4.13	3.33
Suzhou	22.13	24.26	15.72	28.55	29.37	24.00	Huzhou	2.36	2.95	1.51	3.25	3.52	2.71
Changzhou	14.14	15.75	14.89	18.80	20.14	16.74	Xuancheng	2.50	2.76	1.31	3.22	3.51	2.66
Taizhou	11.99	13.36	8.17	15.54	15.55	12.92	Taizhou	1.76	1.97	2.47	2.13	2.27	2.12
Shaoxing	9.76	11.51	7.82	13.42	13.86	11.27	Tongling	1.30	2.14	1.83	2.55	2.25	2.01
Overall average	19.25	21.83	17.48	26.10	27.63	22.46							

Source: By authors.

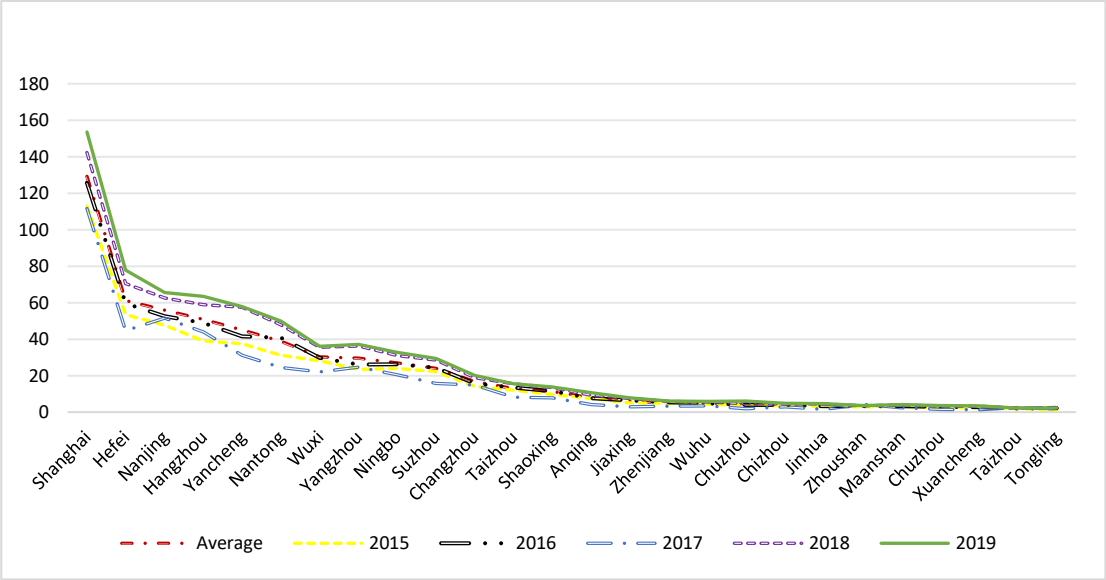

Figure 1. Intensity of spatial interactions between cities in the Yangtze River Delta urban agglomeration and the Beijing-Tianjin-Hebei urban agglomeration from 2015 to 2019
Source: By authors.

(1) The spatial interaction intensity between the Yangtze River Delta urban agglomeration as well as cities within it and the Beijing-Tianjin-Hebei urban agglomeration shows a " vertically steady increase".

Table 1 shows that, globally, the spatial interaction intensity between the Yangtze River Delta and Beijing-Tianjin-Hebei urban agglomerations was respectively 19.25, 21.83, 17.48, 26.10 and 27.63 from 2015 to 2019. Overall, it showed a steady increase to varying degrees. Moreover, the spatial interaction intensity between Shanghai, Hefei, Nanjing and Hangzhou, which are important cities in the Yangtze River Delta city cluster, and the Beijing-Tianjin-Hebei urban agglomeration grows from 112.96, 53.40, 47.59 and 39.00 in 2015 to 153.53, 77.73, 65.96, and 65.15 in 2019, respectively. This indicates that the close connection in the air transportation market effectively promotes the steady increase in spatial interaction intensity between the two areas, becoming an important driving force for the economic development between the Yangtze River Delta and Beijing-Tianjin-Hebei world-class city clusters. As the Yangtze River Delta and Beijing-Tianjin-Hebei urban agglomerations are important "power sources" for China's high-quality economic development, the air transportation industry is able to effectively improve the spatial interaction intensity between the clusters.

(2) The spatial interaction intensity between the Yangtze River Delta urban agglomeration as well as cities within it and the Beijing-Tianjin-Hebei urban agglomeration shows a "horizontal bifurcation ".

Table 1 shows that, by comparing the overall spatial interaction intensity between the 26 cities in the Yangtze River Delta urban agglomeration and the Beijing-Tianjin-Hebei city cluster, the five-year average spatial interaction intensity between Shanghai and the Beijing-Tianjin-Hebei urban agglomeration is as high as 129.19. Hefei, Nanjing, and Hangzhou rank second to fourth with 61.16, 55.93, and 50.81, respectively, but are significantly lower than Shanghai. The overall spatial interaction intensity between 9 cities including Yancheng and the Beijing-Tianjin-Hebei urban agglomeration ranges from 11.27 to 45.08, while for 13 cities such as Anqing, the overall spatial interaction intensity with the Beijing-Tianjin-Hebei urban agglomeration is lower than 10.00. The

main reason for the horizontally significant differentiation is related to factors such as the population density of each city in the city cluster, the flight distance, and the city's economic development level. For this reason, although the development of the air transportation industry in the two areas has significantly improved the spatial interaction intensity between the Yangtze River Delta and Beijing-Tianjin-Hebei city clusters, the differences and similarities in the functional positioning of the airports, the development basis, and the degree of air transportation links between the two areas have led to horizontal differentiation in the spatial interaction intensity between the two city clusters.

3.2 Empirical results of the spatial interaction intensity between cities in the yangtze river delta urban agglomeration and those in beijing-tianjin-hebei city cluster

Table 2 shows the results of the five-year average spatial interaction intensity between cities in the Yangtze River Delta urban agglomeration and those in the Beijing-Tianjin-Hebei" urban agglomeration from 2015 to 2019.

Table 2. Average spatial interaction intensity between cities in the Yangtze River Delta urban agglomeration and those in the Beijing-Tianjin-Hebei" urban agglomeration from 2015 to 2019

Average	Beijing	Tianjin	Shijiazhuang	Handan	Tangshan	Qinhuangdao	Zhangjiakou	Baoding	Langfang	Xingtai	Cangzhou	Hengshui	Chengde
Shanghai	34.93	30.14	15.75	15.46	14.29	4.63	3.60	2.84	2.83	2.00	1.56	0.84	0.32
Nanjing	19.75	17.48	9.77	0.76	1.28	2.34	0.14	1.42	1.45	0.24	0.74	0.41	0.15
Yancheng	18.17	17.20	5.00	0.21	1.00	0.13	0.10	1.06	1.23	0.08	0.58	0.21	0.11
Hefei	17.41	15.15	9.86	12.83	1.06	0.17	0.11	1.26	1.25	0.97	0.62	0.36	0.12
Nantong	14.78	13.13	5.45	0.70	1.01	0.26	0.11	1.07	1.14	0.22	0.6	0.27	0.12
Hangzhou	14.59	12.36	6.60	6.69	4.70	1.23	0.14	1.25	1.22	0.89	0.69	0.33	0.14
Wuxi	12.95	11.35	0.99	0.71	0.92	0.50	0.10	0.81	1.02	0.21	0.54	0.12	0.11
Yangzhou	11.73	10.7	3.64	0.17	0.71	0.20	0.07	0.77	0.83	0.07	0.41	0.17	0.08
Changzhou	10.68	2.20	0.87	0.32	0.44	0.22	0.08	0.68	0.79	0.11	0.21	0.10	0.05
Ningbo	9.79	8.20	4.28	0.77	0.89	0.28	0.10	0.88	0.86	0.23	0.23	0.27	0.11
Suzhou	8.28	6.61	1.86	1.45	1.60	0.49	0.12	1.49	0.83	0.40	0.55	0.20	0.12
Anqing	5.07	1.08	0.28	0.20	0.19	0.05	0.04	0.23	0.42	0.07	0.12	0.04	0.03
Taizhou	4.33	3.50	1.87	0.21	0.30	0.14	0.06	1.54	0.42	0.08	0.26	0.14	0.06
Shaoxing	3.29	2.60	1.41	1.30	1.00	0.27	0.05	0.39	0.34	0.27	0.20	0.09	0.05
Zhenjiang	2.33	0.72	0.56	0.17	0.19	0.14	0.04	0.45	0.24	0.06	0.10	0.06	0.02
Chizhou	1.79	1.51	0.05	0.08	0.13	0.02	0.01	0.08	0.14	0.03	0.08	0.01	0.02
Jiaxing	1.66	1.35	0.71	0.63	0.53	0.14	0.04	0.24	0.19	0.17	0.15	0.06	0.04
Wuhu	1.56	1.19	0.21	0.34	0.21	0.18	0.03	0.54	0.17	0.10	0.13	0.07	0.03
Zhoushan	1.52	1.29	0.05	0.06	0.13	0.02	0.02	0.13	0.13	0.02	0.08	0.01	0.02
Taizhou	1.29	0.19	0.11	0.09	0.11	0.02	0.01	0.09	0.11	0.03	0.03	0.02	0.01
Chuzhou	1.19	0.89	0.51	0.31	0.16	0.12	0.03	0.42	0.14	0.09	0.10	0.05	0.03
Maanshan	1.05	0.81	0.45	0.18	0.13	0.02	0.02	0.37	0.11	0.06	0.08	0.04	0.02
Jinhua	1.01	0.63	0.42	0.35	0.30	0.08	0.03	0.17	0.13	0.11	0.10	0.05	0.03
Huzhou	0.86	0.48	0.26	0.22	0.19	0.05	0.02	0.11	0.08	0.33	0.06	0.03	0.02
Xuancheng	0.82	0.62	0.35	0.11	0.11	0.09	0.02	0.29	0.09	0.04	0.07	0.04	0.02

Tongling	0.76	0.59	0.12	0.09	0.09	0.03	0.01	0.11	0.05	0.03	0.09	0.02	0.01

Source: By authors.

(1) The spatial interaction intensity between Shanghai and Beijing is significantly better than that between other cities in the Yangtze River Delta and Beijing-Tianjin-Hebei city clusters.

Table 2 shows that the spatial interaction intensity between Shanghai and Beijing is significantly better than that between other cities from 2015 to 2019. In 2019, for example, the spatial interaction intensity between Shanghai and Beijing, Tianjin, Shijiazhuang, and non-hub cluster cities within the Beijing-Tianjin-Hebei urban agglomeration was 43.81, 31.26, 18.77 and 5.97, respectively, which were far higher than that of other cities within the Yangtze River Delta city cluster. It can be found through a comparative analysis that Shanghai is the city with the most significant economic radiation and driving effect on the Beijing-Tianjin-Hebei urban agglomeration among the 13 cities within the Yangtze River Delta city cluster. It can be seen that Shanghai, as an important international aviation hub city, serves as China's most important economic center. While undertaking the important task of connecting China with the world, it relies on the most developed air route network in China to effectively support the "power source" function of high-quality economic development in the Yangtze River Delta region.

(2) Significant differences in the average spatial interaction intensity between cities in the Yangtze River Delta and Beijing-Tianjin-Hebei city clusters.

According to the average spatial interaction intensity between city pairs from 2015 to 2019, the spatial interaction intensity of Shanghai, Nanjing, Yancheng, and Hefei with Beijing accounted for 44.8% of the total intensity of the Yangtze River Delta urban agglomeration with Beijing; and the spatial interaction intensity of cities in the Yangtze River Delta urban agglomeration with Beijing, Tianjin, and Shijiazhuang accounted for 74.5% of the total intensity of the Beijing-Tianjin-Hebei (Beijing-Tianjin-Hebei) city cluster, which was significantly stronger than that with other cities in the Beijing-Tianjin-Hebei city cluster. This shows that there are obvious differences in the spatial interaction intensity between the 26 cities in the Yangtze River Delta urban agglomeration and the cities in the Beijing-Tianjin-Hebei city cluster, and the Yangtze River Delta urban agglomeration can realize a steady increase in the spatial interaction intensity with the Beijing-Tianjin-Hebei urban agglomeration by relying on the economically developed airport cities, while the other cities in the cluster play a complementary role in the increase of the spatial interaction intensity between the two city clusters.

3.3 Spatial interaction intensity between cities hosting airports of different hub levels in the yangtze river delta and beijing-tianjin-hebei city clusters

In this paper, the two urban agglomerations are divided into 39 cities based on three hub levels, namely, international aviation hub, regional aviation hub, and non-hub cluster. Given that the intensity of spatial interactions is not significant for individual non-hub cluster cities, they are considered collectively as non-hub cluster cities. In contrast, international and regional hub airport cities are studied separately, and the spatial interaction intensity of city pairs with different aviation hub levels are compared (as shown in Table 3), so as to better reflect the impact of the differences in the level of air transportation development on the spatial interaction intensity.

Table 3. Analysis of spatial interaction intensity between cities hosting airports of different hub levels in the Yangtze River Delta and Beijing-Tianjin-Hebei city clusters

	Shanghai - Beijing	Shanghai - Tianjin	Shanghai - Shijiazhuang	Shanghai - non-hub cluster	Nanjing - Beijing	Nanjing - Tianjin	Nanjing - Shijiazhuan	Nanjing - non-hub cluster
2015	27.89	26.21	14.45	4.44	15.64	15.08	8.89	0.80
2016	31.48	29.18	16.08	4.89	17.40	16.55	9.76	0.88
2017	34.29	31.12	12.31	3.38	19.43	18.09	7.65	0.63
2018	37.17	32.94	17.13	5.50	21.53	19.58	10.89	1.05
2019	43.81	31.26	18.77	5.97	24.74	18.11	11.63	1.11
	Hefei - Beijing	Hefei - Tianjin	Hefei - Shijiazhuan	Hefei - non-hub cluster	Hangzhou - Beijing	Hangzhou - Tianjin	Hangzhou - Shijiazhuan	Hangzhou - non-hub cluster
2015	13.91	13.24	9.00	1.73	11.42	10.56	5.93	1.11
2016	15.70	14.74	10.02	1.90	13.00	11.85	6.66	1.73
2017	14.47	13.30	6.49	1.04	13.91	12.41	5.00	1.26
2018	19.50	17.51	11.23	2.23	15.90	13.86	7.35	2.23
2019	23.46	16.96	12.56	2.47	18.71	13.13	8.04	2.47
	Ningbo - Beijing	Ningbo - Tianjin	Ningbo - Shijiazhuan	Ningbo - non-hub cluster	non-hub cluster - Beijing	non-hub cluster - Tianjin	non-hub cluster - Shijiazhuan	non-hub cluster - non-hub cluster
2015	8.10	7.41	4.04	0.43	4.28	3.51	0.61	0.41
2016	9.00	8.12	4.43	0.47	4.76	3.84	0.97	0.40
2017	8.03	7.09	2.78	0.25	3.76	2.90	0.85	0.17
2018	11.05	9.53	4.91	0.56	5.74	4.45	1.75	0.29
2019	12.75	8.85	5.26	0.59	6.48	4.03	1.83	0.24

Source: By authors.

Between 2015 and 2019, as the functions of air transportation gradually improved, the average spatial interaction intensities between non-hub cluster cities in the Yangtze River Delta urban agglomeration and the Beijing-Tianjin-Hebei urban agglomeration were 8.81, 9.97, 7.68, 12.23, 12.58, respectively, and that between the regional air hub cities Nanjing, Hefei, Hangzhou, and Ningbo and the Beijing-Tianjin-Hebei urban agglomeration were 31.82, 35.55, 32.96, 42.23, 45.21, respectively, while the spatial interaction intensities between the international aviation hub city Shanghai and Beijing-Tianjin-Hebei urban agglomeration were 72.99, 81.36, 81.1, 92.74, 99.81, respectively. This shows that the spatial interaction intensities between international hubs, regional aviation hubs, and non-hub cluster cities in the Yangtze River Delta urban agglomeration and the Beijing-Tianjin-Hebei urban agglomeration have shown a vertically steady increase as a whole. The development of the air transportation industry has shortened the spatial and temporal distance between the two world-class city clusters, accelerated the improvement of spatial interaction intensity, and significantly utilized the advantages of civil aviation among the city clusters, which, to a certain extent, has promoted the economic interactions among the aviation hubs in the Yangtze River Delta and Beijing-Tianjin-Hebei city clusters.

(2) The results show that the spatial interaction intensity between international aviation hubs in the Yangtze River Delta urban agglomeration and each city hosting aviation hubs in the Beijing-Tianjin-Hebei urban agglomeration is better than that of regional aviation hubs as well as non-hub clusters within the Yangtze River Delta city cluster. In 2019, for example, the spatial interaction intensities between the international aviation hub city Shanghai, the four regional aviation hub cities Nanjing, Hefei, Hangzhou, and Ningbo, and the non-hub cluster cities in the Yangtze River Delta urban agglomeration and Beijing were 43.81, 19.95, and 6.48, respectively; and the spatial interaction intensities with Tianjin were 31.26, 14.26, and 4.03, respectively. It can be seen that there is an overall "differentiated gradient" characteristic in the spatial interaction intensities between international and regional aviation hubs, and non-hub cluster cities in the Yangtze River Delta urban agglomeration

and the Beijing-Tianjin-Hebei city cluster. This shows a trend of decreasing gradients, with significant differences between different levels.

(3) It can be seen from Table 3 that the spatial interaction intensities between the international aviation hub, regional aviation hubs, and non-hub cluster cities and Beijing reached 99.81, 45.21 and 12.58 respectively in 2019, and the spatial interaction intensity between cities hosting airports of different aviation hub levels in the Yangtze River Delta and Beijing-Tianjin-Hebei urban agglomerations showed a spatial characteristic of "gradient decline", but the overall spatial interaction intensity between cities hosting airports of different aviation hub levels in the two urban agglomerations is relatively stable. Between 2015 and 2019, the overall spatial interaction intensities between the international, regional, and non-hub cluster cities in the Yangtze River Delta urban agglomeration and the hub cities in the Beijing-Tianjin-Hebei urban agglomeration remained relatively stable, consistently ranking first, second, and third respectively, and showing a "three-tiered" situation without any significant fluctuations.

Using the Yangtze River Delta city cluster as a reference, the air distance serves as a significant advantage in comparing air transportation. The enhanced gravitational model, grounded on air distance, can more objectively reflect the spatial interaction strength of the Yangtze River Delta-Beijing-Tianjin-Hebei city cluster. This approach carries considerable theoretical significance and value in promoting the spatial interaction strength of the Yangtze River Delta-Beijing-Tianjin-Hebei city cluster. Assessing the spatial interaction strength between the "Yangtze River Delta-Beijing-Tianjin-Hebei" city clusters holds substantial theoretical significance and value. However, this study has some limitations. The research scope is relatively narrow, focusing on the two core urban agglomerations of the Yangtze River Delta and Beijing-Tianjin-Hebei in China. The selected enhanced gravity model does not take into account the frequency of flights, passenger traffic, and other indicators. Moreover, the study uses data from 2015-2019, prior to the pandemic, without expanding the research years for analysis. Therefore, the paper possesses certain limitations. In future studies, we aim to broaden the scope of the research object, increase the span of research years, expand the range of indicator selection, and conduct research on the spatial interaction strength between world-class airports in China's urban agglomerations.

4. Conclusions and Policy Suggestions

Scientific measurement of the spatial interaction intensity of the Yangtze River Delta and Beijing-Tianjin-Hebei urban agglomerations is an important support for optimizing the design of the air route networks between the two regions. Based on the year-end population, GDP, and other indicators of 39 cities in the Yangtze River Delta and Beijing-Tianjin-Hebei city clusters, this paper constructs a distance-corrected gravity model based on different modes of transportation, and conducts a quantitative study of the spatial interaction intensities of the 39 cities in the two world-class urban agglomerations from 2015 to 2019 to provide a basis for the optimization of air route networks between the Yangtze River Delta and Beijing-Tianjin-Hebei city clusters. Our findings show that the spatial interaction intensity between the Yangtze River Delta urban agglomeration and its internal cities and the Beijing-Tianjin-Hebei urban agglomeration is characterized by "vertically steady increase and horizontally prominent difference", while the spatial interaction intensity between different hub-level airports in the Yangtze River Delta and Beijing-Tianjin-Hebei urban agglomerations shows a characteristic of " vertically steady increase and horizontally gradient decline".

As a result, in order to further optimize and intensify the high-quality air route network between the Yangtze River Delta region and the Beijing-Tianjin-Hebei region, to promote the economic interconnection and enhancement among the world-class city clusters, and to realize the requirements of Chinese-style modernization and high-quality development of civil aviation, this paper proposes the following suggestions and measures based on the three major aviation hubs in the Yangtze River Delta city cluster:

(1) International aviation hubs in the Yangtze River Delta urban agglomeration need to lead the construction of regional aviation hubs and consolidate the development of route networks for international aviation hubs. As Shanghai is the most important dual-hub airport in the Yangtze River Delta region, and the Shanghai-Beijing route is the most important connection between the Yangtze River Delta and Beijing-Tianjin-Hebei city clusters, it is necessary to strengthen Shanghai as an international aviation hub to lead the development of regional aviation hubs and regional aviation networks within the Yangtze River Delta city cluster. In the future, it is necessary to strengthen Shanghai as an international aviation hub to lead the development of regional aviation hubs and non-hub clusters in the Yangtze River Delta city cluster, to improve the service capacity for key route markets such as Beijing, Tianjin and Shijiazhuang, and to consolidate and deepen the brand effect of efficient and stable routes. Moreover, it is necessary to promote the coordinated development between the two international hub airports in Shanghai within the Yangtze River Delta urban agglomeration and the neighboring trunk and feeder routes, further enhance the width and depth of high-quality air express routes between Shanghai and Beijing, vigorously promote the construction of route networks between Shanghai and Tianjin, Shijiazhuang, and focus on increasing flight frequencies.

(2) Regional aviation hubs need to focus on developing high-quality air routes between important cities in the Beijing-Tianjin-Hebei city cluster, and undertake the overflow function of international aviation hubs in the Yangtze River Delta city cluster.

Nanjing, Hefei, Hangzhou and Ningbo, as the four major regional aviation hubs in the Yangtze River Delta city cluster, need to focus on increasing the air routes between them and Beijing, and create high-standard "flight express routes" between the aviation hub gateways within the two urban agglomerations such as the "Ningbo-Beijing Express", " Hefei-Beijing Express", "Hangzhou-Beijing Express" and "Ningbo-Beijing Express". It is necessary to significantly increase the high-quality routes between Nanjing, Hefei, Hangzhou, and Ningbo and the regional aviation hubs of Tianjin and Shijiazhuang in the Beijing-Tianjin-Hebei city cluster, and construct and intensify an air route network between the Yangtze River Delta and Beijing-Tianjin-Hebei urban agglomerations that is well-connected, with high accessibility, and wide coverage. In addition, regional aviation hubs and international aviation hubs within the Yangtze River Delta urban agglomeration need to achieve coordinated development, undertake the overflow function of international aviation hubs, and create a mutually beneficial and coordinated situation between the two.

(3) Make full use of international and regional aviation hubs in the Yangtze River Delta urban agglomeration to drive the development of non-hub cluster cities. Since non-hub cluster airports in the Yangtze River Delta urban agglomeration have little civil aviation traffic and low spatial interaction intensity with the Beijing-Tianjin-Hebei city cluster, it is necessary to make full use of international and regional aviation hubs to drive the construction of non-hub cluster cities, as well as innovate comprehensive transportation modes and optimize the ground transportation from non-hub cluster cities to nearby cities with flights. At the same time, it is necessary to improve the spatial network structure of air transportation between non-hub cluster airports and the Beijing-Tianjin-Hebei airport cluster, strengthen and innovate the route network mode of "trunk and branch, full

network connection", and combine "trunk and trunk ", "trunk and branch", "branch and branch", and "branch-through" effective joint, and actively open up and intensify the non-hub cluster cities to the Beijing-Tianjin-Hebei urban agglomeration routes with high spatial interaction intensity, wider scope, more reasonable structure, so as to realize differentiated competition in the route network, increase government subsidies for feeder routes and the allocation of civil aviation resources to non-hub cluster cities, thereby promoting the high-quality development of civil aviation and the coordinated development of the regional economy.

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① [Notes]:39 cities are Anqing, Baoding, Beijing, Cangzhou, Changzhou, Chengde, Chizhou, Chuzhou, Handan, Hangzhou, Hefei, Hengshui, Huzhou, Jinhua, Jiaxing, Langfang, Maanshan, Nanjing, Nantong, Ningbo, Qinhuangdao, Shanghai, Shijiazhuang, Shaoxing, Suzhou, Taizhou, Taizhou, Tangshan, Tianjin, Tongling, Wuxi, Wuhu, Xingtai, Xuancheng, Yancheng, Yangzhou, Zhangjiakou, Zhenjiang Zhoushan (in alphabetical order).