Research on the Optimization of Air Route Network in Henan Province from the Perspective of Spatial Interaction Intensity-Taking the Four World-class Airport Clusters as Examples

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DOI: https://doi.org/10.30210/JMSO.202402.002

ABSTRACT

Scientific assessment of the spatial interaction intensity between Henan Province and the four world-class airport clusters based on air transportation is an important basis for leveraging the region's radiation function as a 'power source' of high-quality economic development. This aims to promote regional coordinated development and optimize the air route network in Henan province. Based on the improved gravity model of flight frequency, this paper quantitatively measures the spatial interaction strength between the four airport cities in Henan Province and cities in China's four world-class airport clusters from 2015 to 2019, upon which the air route network connection is optimized. The findings reveal that the spatial interaction intensity between the airport cities in Henan province and the four world-class airport clusters exhibits a trend of "vertical steady improvement and horizontal polarization" overall, while the spatial interaction intensity between the four airport cities and cities in the four airport clusters demonstrates a "gradient pattern of differentiation." In the future, Henan should fully leverage the air transportation industry to strengthen economic ties with the four world-class airport cluster cities, taking full advantages of the radiating and driving effects of "power sources" such as the Yangtze River Delta, Zhengzhou, Luoyang, Nanyang, and Xinyang should strengthen differentiated connections with the four major world-class airport clusters through aviation transportation networks. In addition, Henan province should promote centralized and unified management of airports within the province to achieve coordinated "trunk and branch" development.

Keywords: World-Class airport cluster, Spatial interaction, Coordinated regional development, Air Route Network Optimization.

1.Introduction

Promoting coordinated regional development has always been central to China's approach in allocating spatial resources and optimizing economic patterns [1,2]. Related studies show that the trend of narrowing the regional gap between East, Middle, and West China is weakening or even stagnating, which is not compatible with the requirements of China's new stage of development, nor with China's concept of shared development [3,4]. Therefore facilitating coordinated regional development will continue to be an important part of China's modernization construction. General Secretary Xi Jinping emphasized that "It is a fundamental economic principle that industries and populations tend to concentrate in advantageous regions, giving rise to urban agglomerations as the primary source of growth momentum, thereby enhancing overall economic efficiency." Beijing-Tianjin-Hebei, Yangtze River Delta, Guangdong-Hong Kong-Macao Greater Bay Area, and Chengdu-Chongqing Twin-City Economic Circle have become important power sources for China's high-quality economic development because of their active economic development, high degree of openness, and strong innovation capacity, playing an important role in regional development [5]. Transportation can effectively promote the balanced allocation and flow of production factors, improving the objectively passive situation of inter-regional cooperation [6,7], and thus play a significant role in promoting coordinated regional development. Holding a similar view, Hu concluded that the rational development of transportation network in urban agglomerations is of great significance in promoting the coordinated allocation of regional resources [8]. Additionally, air transportation is an important part of China's economic growth "gas pedal" due to its comparative advantage of high efficiency and convenience, which can greatly shorten the distance between cities, break the market segmentation between regions, and increase the degree of spatial connection among cities [9,10,11].

Henan, as a vital component of China's Central Region Revitalization Strategy [12], is still facing challenges such as low efficiency in economic growth and the pressing need for optimization of the economic structure [13]. Consequently, the local community is confronted with the practical issue of promoting high-quality economic development through adapting to changes scientifically and proactively seeking solutions [14]. Zhao asserted that Henan, along with other regions, should actively employ its comparative advantages to integrate into the national major regional strategies, while harnessing the supporting role of world-class urban clusters to effectively promote high-quality development in the central region [15]. It has been proven that the central region's GDP share and per capita GDP rankings have shown a significant upward trend since 2010 after the implementation of coordinated regional development and other major strategies [16]. The fast transportation system and complete transportation infrastructure are the key breakthroughs for Henan to integrate into China’s coordinated regional development strategy and to solve the challenges of local economic development. Air transportation plays a unique role in promoting the transformation and upgrading of the regional economic structure and driving the overall economic and social development due to its comparative advantages [17,18]. Furthermore, the "14th Five-Year" Civil Aviation Development Plan clearly requires the central region to utilize its geographical advantages, accelerate the construction of aviation hubs and channels, and create a strategic pivot point for the domestic circulation, thus providing an opportunity for Henan's aviation sector to fully leverage its comparative advantages. Policy guidelines provided by the "14th Five-Year" Civil Aviation Development Plan help Henan Aviation realize its comparative advantages.

Related studies have shown that scientific design of route networks is not only the basis for the sustained and healthy growth of air transportation business but also an important guarantee for air transportation to support the development of the local economy [19,20]. The spatial interactions theory plays crucial role in guiding the spatial resource allocation and regional division of labor [21,22], and is often used to analyze the urban traffic flow, air transport flow and road transport flow, providing important ideas for the design and optimization of route networks. This theory is commonly employed in the field of transportation to analyze aspects such as urban traffic flow, air transportation flow, and highway transportation flow, offering crucial insights for the design and optimization of route networks [23,24].

Therefore, this paper draws on existing research to construct an "improved gravity model based on flight frequency" using spatial interaction theory to quantitatively measure the strength of spatial interactions between the four airport cities in Henan Province and the four world-class airport clusters. It aims to optimize the connectivity of their air route networks accordingly, thus providing reference for the integration of Henan into the national strategy and promoting the quality development of the regional economy. This research will offer guidance for the integration of Henan Province into the national strategy and leverage the economic driving effect of the "power source" regions such as Beijing, Tianjin, and Hebei, thereby promoting the high-quality development of the regional economy.

2. Research Design

2.1 Selection of research objects and data sources

Acknowledging the notable impact of the Covid-19 epidemic on China's air transportation industry in the early 2020s, this study confines its time frame to 2015-2019. In contrast to other studies that may rely solely on data from a single year or a shorter period, this research utilizes spanning a longer duration, enabling a more comprehensive understanding of the evolving trends in spatial interaction intensity.Additionally, this paper specifically concentrates on the four airport cities: Zhengzhou, Luoyang, Nanyang, and Xinyang (which commenced commercial operation in 2018) alongwith 42 cities situated within the 47 airports of Beijing-Tianjin-Hebei Airport Cluster, Chengdu-Chongqing Airport Cluster, Yangtze River Delta Airport Cluster, and Guangdong-Hong

Kong-Macao Greater Bay Area Airport Cluster1. Furthermore, the relevant flight frequency data in this paper are sourced from the Civil Aviation Statistical Yearbook of China for 2016-2020, while the gross regional product and population size data are obtained from the Urban Statistical Yearbook of China for the corresponding years.

2.2 Measurement of the strength of spatial interactions

The theory of spatial interaction was first proposed by American geographer Ullman [21]. With the diversification and complexity of inter-city factor flows, scholars have continuously revised the gravity model from different perspectives such as city quality, inter-city distance and gravity coefficient.

This study constructs an improved gravity model based on flight frequency. This model not only represents the degree of connectivity between airport cities but also mirrors the activity and development potential of the air transportation market. Thus, the calculation results more directly reflect the actual activity of air transportation. The specific formula is as follows:

$$R_i = \sum_{i=1}^{n-1} R_{ij} \quad [1]$$

$$R_{ij} = N_{ij} * \frac{\sqrt{P_i} * \sqrt{P_j}}{T_{ij} * T_{ij}} \quad [2]$$

$$P_j = \sqrt{GDP_j * POP_j} \quad [3]$$

R_i: stands for the total spatial interaction strength of city i. The larger R_i is, the greater spatial interaction between city i and the world-class airport cluster, indicating closer economic ties.

R_{ij}: stands for the relationship between the spatial interaction strength between city i (i=1,2,3,4) of Henan airport and city j (j=1,2,3 ...... .42) of world-class airport clusters. It reflects the intensity of spatial interaction between city i and city j. The larger R_{ij} is, the higher intensity of economic linkage between city i and city j is.

P_i and P_j stand for the quality of city i and city j, reflecting the city's economic radiation capacity and attractiveness. In this paper, we use the regional gross city product (GDP) and population size (POP) as indicators of quality.

N_{ij} stands for the sum of the flight frequencies in three cases of departure, transit and arrival between city i of Henan airport and city j of world-class airport cluster every year. if there is no direct or stopover flight between two cities, the flight frequency is assigned as 1.

T_{ij} stands for the shortest air travel time (min) from city i of Henan airport to city j of world-class airport cluster.

(1) For direct and stopover flights, the Great Circle Mapper calculates the route distance between airports. The design cruise speed of the Boeing 747 is then used as the airspeed per hour. The shortest travel time is determined by dividing the distance by the hourly speed. For stopover

Due to the differences in the rules governing civil aviation in Hong Kong and Macao, this study does not cover air transportation market research in the two special administrative regions.

flights, an additional 45 minutes is added to account for transit time.

(2) If there are no direct flights available, MATLAB software is utilized to calculate the minimum required travel time.

3 Empirical Results and Analysis

3.1 Analysis of the evaluation results of spatial interaction strength between airport cities in Henan province and world-class airport cluster cities

Table 1 represents the evaluation results of the spatial interaction strength between airport cities in Henan province and cities in the world-class airport clusters. According to Table 1, the total spatial interaction intensity between airport cities in Henan province and the cities in the world-class airport cluster presents a situation of "vertical steady improvement", "horizontal polarization" and "obvious spatial differences".

(1) The spatial interaction intensity between airport cities in Henan province and cities in the four world-class airport clusters shows a 'vertical steady improvement'.

1) The total spatial interaction intensity between the four airport cities in Henan province and cities in the Yangtze River Delta Airport Cluster, Chengdu-Chongqing Airport Cluster, Guangdong-Hong Kong-Macao Greater Bay Area Airport Cluster, and Beijing-Tianjin-Hebei Airport Cluster has increased respectively from 313.2032, 153.6856, 70.6918, and 107.5290 in 2015 to 407.0595, 283.3897, 144.7918, and 108.6462 in 2019. This demonstrates the increasing significance of air transportation in enhancing economic connectivity and fostering economic collaboration between Henan Province and cities within global airport clusters. Henan can strategically leverage the influence of the Yangtze River Delta and other economically vibrant regions across China as catalysts for regional economic growth through air travel. By doing so, it can effectively advance local economic development and contribute to the realization of the national strategy for coordinated regional development.

2) The total spatial interaction intensity between Zhengzhou and the other four airport cities as well as the world-class airport cluster cities, has notably increased. Specifically, the total spatial interaction intensity between Zhengzhou, Nanyang, and Luoyang and the world-class airport cluster cities increased respectively from 561.2663, 33.7148, and 50.1285 in 2015 to 757.3488, 73.2484, and 69.3026 in 2019. Additionally, the total spatial interaction intensity between Xinyang and the world-class airport cluster cities surged from 6.2616 in 2018 to 43.9875 in 2019. These findings underscore the pivotal role of air transportation in driving external economic development and fostering robust collaboration in foreign economic cooperation. Cities like Zhengzhou are increasingly reaping the benefits of economic radiation and the catalytic effects originating from dynamic regions such as the Yangtze River Delta, serving as vital contributors to high-quality economic development.

Table 1 Evaluation results of spatial interaction intensity between airport cities in Henan province and world-class airport cluster cities from 2015 to 2019

Airport City - World Class Airport Cluster/year		2015	2016	2017	2018	2019
Four airport cities in Henan province-	Yangtze River Delta airport cluster	313.2032	327.8698	326.4390	319.3650	407.0595
	Chengdu-Chongqing airport cluster	153.6856	187.9781	234.2174	227.3290	283.3897
	Guangdong-Hong Kong-Macao Greater Bay Area airport cluster	70.6918	87.5653	98.5297	123.0913	144.7918
	Beijing-Tianjin-Hebei airport cluster	107.5290	76.9847	82.6480	95.4802	108.6462
Zhengzhou -	Yangtze River Delta airport cluster	292.2697	304.3057	303.5558	289.3558	356.2467
	Chengdu-Chongqing airport cluster	142.0167	172.6200	211.1098	197.0047	218.2747
	Guangdong-Hong Kong-Macao Greater Bay Area airport Cluster	59.3917	73.9382	84.3066	107.7783	125.4102
	Beijing-Tianjin-Hebei airport Cluster	67.5882	44.1723	47.8434	53.1176	57.4173
	Total	561.2663	595.0363	646.8156	647.2564	757.3488
Luoyang-	Chengdu-Chongqing airport cluster	7.7757	10.8213	6.4353	13.3354	22.9527
	Beijing-Tianjin-Hebei airport Cluster	27.9949	18.6761	20.3114	24.0218	22.7454
	Yangtze River Delta airport cluster	12.3013	13.9984	13.0678	17.0636	19.0743
	Guangdong-Hong Kong-Macao Greater Bay Area airport Cluster	2.0566	3.5344	3.1369	3.7683	4.5302
	Total	50.1285	47.0302	42.9515	58.1890	69.3026
Nanyang-	Chengdu-Chongqing airport cluster	3.8931	4.5368	16.6722	14.8188	25.7535
	Beijing-Tianjin-Hebei airport cluster	11.9459	14.1362	14.4932	17.3024	21.9313
	Yangtze River Delta airport cluster	8.6322	9.5657	9.8155	10.2871	12.8734
	Guangdong-Hong Kong-Macao Greater Bay Area airport cluster	9.2435	10.0927	11.0862	11.1502	12.6902
	Total	33.7148	38.3315	52.0671	53.5586	73.2484
Xinyang-	Yangtze River Delta airport cluster	-	-	-	2.6584	18.8651
	Chengdu-Chongqing airport cluster	-	-	-	2.1702	16.4089
	Beijing-Tianjin-Hebei airport cluster	-	-	-	1.0385	6.5523
	Guangdong-Hong Kong-Macao Greater Bay Area airport cluster	-	-	-	0.3945	2.1611

Total	-	-	-	6.2616	43.9875

Source: By authors.

(2) The spatial interaction intensity between airport cities in Henan province and cities in the four world-class airport clusters is "horizontal polarization".

A polarized pattern emerges among airport cities in Henan Province in utilizing the economic radiation-driven role of the cities in the four world-class airport clusters.In 2015, the total spatial interaction intensity between airport cities in Henan Province and the cities in the Yangtze River Delta airport cluster was 2.04 times that of the Chengdu-Chongqing airport cluster, 2.91 times that of the Beijing-Tianjin-Hebei airport cluster, and 4.43 times that of the Guangdong-Hong Kong-Macao Greater Bay Area airport cluster, respectively. In contrast, these figures were 1.44 times, 3.75 times, and 2.81 times in 2019. This shows a significant "polarization pattern" in Henan's utilization of the radiation-driven economic development of the Yangtze River Delta, Chengdu-Chongqing, Guangdong-Hong Kong-Macao Greater Bay Area, and Beijing-Tianjin-Hebei region through air transportation. This indicates that the comparative advantage of air transportation depends significantly on spatial distance, which is crucial for Henan's development. Furthermore, it highlights the importance of the objective differences in spatial distance between airport cities in Henan province and the four world-class airport clusters as a key factor influencing the significant disparities in spatial interaction intensity between Henan province and the airport clusters in terms of air transportation.

(3) The spatial interaction intensity between airport cities in Henan province and cities in the four world-class airport clusters shows "obvious spatial differences".

First, Zhengzhou's spatial interaction strength with world-class airport cluster cities is significantly better than that of other airport cities. As presented in Table 1, the total spatial interaction intensity between Zhengzhou and the four world-class airport cluster cities is significantly higher than that of Luoyang, Nanyang, and Xinyang from 2015 to 2019. For example, Zhengzhou's total spatial interaction strength with world-class airport cluster cities is 10.34 times that of Nanyang, 10.93 times that of Luoyang, and 17.22 times that of Xinyang in 2019. In addition, Zhengzhou also has a significant comparative advantage in terms of spatial interaction intensity; for example, in 2019, the total spatial interaction intensity between Zhengzhou and the Yangtze River Delta Airport Cluster cities is respectively 27.68 times that of Nanyang, 18.68 times that of Luoyang, and 18.88 times that of Xinyang. This shows that Zhengzhou is significantly better than other airport cities such as Luoyang in utilizing air transportation to leverage the radiation and driving effect of the Yangtze River Delta and other economic "power sources".

Second, the spatial interaction intensity between Zhengzhou, Luoyang, Nanyang, and Xinyang and cities in the world-class airport clusters has a significant difference in pattern distribution. As shown in Table 1, the spatial interaction intensity between Zhengzhou and the cities within the Yangtze River Delta airport cluster, Chengdu-Chongqing airport cluster, Guangdong-Hong Kong-Macao Greater Bay Area airport cluster, and Beijing-Tianjin-Hebei airports presents a gradient decreasing distribution. The spatial interaction strength of Luoyang and Nanyang with cities in Chengdu-Chongqing airport cluster, Beijing-Tianjin-Hebei airport cluster, Yangtze River Delta airport cluster, and Guangdong-Hong Kong-Macao Greater Bay Area airport cluster shows a gradient decreasing distribution. The spatial interaction intensity between Xinyang and the cities in the Yangtze River Delta airport cluster, Chengdu-Chongqing airport cluster, Beijing-Tianjin-Hebei airport cluster, and Guangdong-Hong Kong-Macao Greater Bay Area airport cluster shows a gradual decrease in the distribution of spatial interaction intensity.

3.2 Analysis of the evaluation results of spatial interaction strength between zhengzhou and the world-class airport cluster cities

Table 2 shows the evaluation results of spatial interaction strength between Zhengzhou and the cities in the four world-class airport clusters in China. According to Table 2, the spatial interaction intensity between Zhengzhou and the cities in the four world-class airport clusters is characterized as follows:

(1) The spatial interaction strength between Zhengzhou and the cities in the Yangtze River Delta airport cluster is characterized by "consistent vertical improvement, one core, one main point and many points".

The overall spatial interaction strength between Zhengzhou and the cities in the Yangtze River Delta airport cluster shows a steady increase. The spatial interaction intensity between Zhengzhou and Shanghai (an international aviation hub city), Hangzhou, Ningbo, Wenzhou (a regional aviation hub city), and Nantong (a non-hub city), grows respectively from 133.2625, 63.6534, 9.3159, 9.5534, 0.7380 in 2015 to 154.6076, 87.8421, 18.4655, 14.8558, 14.4371 in 2019. It can be seen that Shanghai has become the "core city" with the strongest economic driving capability in the Yangtze River Delta airport cluster cities for Zhengzhou to utilize aviation transportation for radiation. Hangzhou follows closely as the "major city," ranking second after Shanghai. Additionally, cities such as Nanjing, Hefei, Ningbo, Wenzhou, Nantong, and others have similar aviation connection strength with Zhengzhou, thus presenting a "multipoint" pattern.

(2) The spatial interaction strength between Zhengzhou and the cities in the Chengdu-Chongqing airport cluster shows a "consistent vertical improvement, a core and a scattering" trend as a whole.

The spatial interaction strength between Zhengzhou and cities in Chengdu-Chongqing airport cluster have shown steady growth, with the spatial interaction strength between Zhengzhou and Chongqing, Chengdu, and Mianyang increased respectively from 111.1102, 30.0512, 0.8531 in 2015 to 167.4495, 39.2684, 6.1349 in 2019. From this, it can be observed that Chongqing is the "core city" with the strongest economic driving capability for Zhengzhou among the cities in the

Chengdu-Chongqing airport cluster, utilizing aviation transportation for radiation. Chengdu, noticeably weaker than Chongqing, becomes a "sub-center city." Other cities in the Chengdu-Chongqing airport cluster, such as Mianyang, Nanchong and Luzhou, have a relatively limited role in positively influencing the economy of Zhengzhou through air transportation, thus presenting a "scattered" situation.

Table 2 Evaluation results of spatial interaction strength between Zhengzhou and world-class airport cluster cities from 2015 to 2019

World-class airport cluster cities/year		2015	2016	2017	2018	2019
Yangtze River Delta	Shanghai	133.2625	138.3578	137.545	146.3343	154.6076
	Hangzhou	63.6534	73.0902	70.9476	28.1828	87.8421
	Nanjing	32.7334	30.9220	27.5969	25.6930	25.8968
	Hefei	40.0075	30.8148	28.4829	21.9883	23.4573
	Ningbo	9.3159	10.1148	11.7509	24.0993	18.4655
	Wenzhou	9.5534	11.9353	13.2952	18.5704	14.8558
	Nantong	0.7380	4.8728	6.2566	10.3004	14.4371
Chengdu- Chongqing	Chongqing	111.1102	130.6743	163.8877	141.0164	167.4495
	Chengdu	30.0512	40.2954	42.8879	49.8002	39.2684
	Mianyang	0.8531	1.5090	4.0483	5.5483	6.1349
Guangdong, Hong Kong and Macao Greater Bay Area	Guangzhou	26.9093	31.0259	35.9475	50.0844	57.549
	Shenzhen	30.2638	39.1086	43.7536	48.1857	57.5416
	Zhuhai	2.2171	3.8017	4.3311	6.5599	6.7761
Beijing-Tianjin-Hebei	Beijing	41.1839	31.0325	31.0590	35.1920	41.5815
	Tianjin	26.3995	11.7352	14.3050	13.7294	11.4873
	Shijiazhuang	0.0022	0.9774	2.1295	2.6369	2.6794
	Qinhuangdao	0.0004	0.4222	0.3461	1.5533	1.6628

(Notes: Due to the limited length of the paper and the polarization of the spatial interaction strength between Zhengzhou and the cities in the world-class airport clusters, this paper only presents the hub cities and the first-ranked non-hub cities.)

Source: By authors.

(3) The spatial interaction intensity between Zhengzhou and the cities in the Guangdong-Hong Kong-Macao Greater Bay Area airport cluster shows a trend of "consistent vertical improvement, with a scattering of the dual core".

The spatial interaction intensity between Zhengzhou and the cities in the Guangdong-Hong Kong-Macao Greater Bay Area airport cluster has increased significantly, with that of Guangzhou, Shenzhen, and Zhuhai increasing respectively from 26.9093, 30.2638 and 2.2171 in 2015 to

57.5490, 57.5416, and 6.7761 in 2019. A comparative analysis reveals that Zhengzhou's spatial interaction intensity with Guangzhou is similar to that with Shenzhen and is in the leading position among the cities in the Guangdong-Hong Kong-Macao Greater Bay Area airport cluster, thus presenting a "dual-core city" situation. On the other hand, the spatial interaction strength between Zhengzhou and Zhuhai, Foshan and other cities is relatively small, and the performance of strength size is uneven, so the overall situation needs further improvement and upgrading.

(4) The spatial interaction intensity between Zhengzhou and the cities in the Beijing-Tianjin-Hebei airport cluster shows a situation of "weak vertical growth, a core of scattered points of differentiation" as a whole.

The growth in spatial interaction intensity between Zhengzhou and cities in the Beijing-Tianjin-Hebei airport cluster has been relatively limited. Specifically, its spatial interaction intensity with Beijing, Tianjin, Shijiazhuang, and Qinhuangdao increased from 41.1839, 26.3995, 0.0022, and 0.0004 in 2015 to 41.5815, 11.4873, 2.6794, and 1.6628 in 2019, respectively. This trend suggests that, due to the rapid development of alternative transportation modes such as high-speed rail networks, air transportation faces challenges in establishing a comparative advantage in medium and short-distance passenger travel. Among the cities in the Beijing-Tianjin-Hebei airport cluster, the spatial interaction intensity between Zhengzhou and Beijing stands out as the highest. However, the spatial interaction intensity between Zhengzhou and Tianjin, Shijiazhuang, and other cities is relatively small, displaying varying degrees of intensity. Overall, there is a need for further improvement and enhancement in spatial interaction across the entire cluster.

3.3 Analysis of the evaluation results of spatial interaction intensity between luoyang, nanyang and xinyang with world-class airport cluster cities

Table 3 presents the evaluation results of spatial interaction strength between Luoyang and Nanyang as well as the cities withinthe four world-class airport clusters, Meanwhile Table 4 displays the evaluation results of spatial interaction strength between Xinyang and the cities within the same airport clusters.

Table 3 Evaluation results of spatial interaction intensity between Luoyang and Nanyang with the world-class airport cluster cities from 2015 to 2019

World-class airport cluster		Luoyang					Nanyang				
cities/year		2015	2016	2017	2018	2019	2015	2016	2017	2018	2019
Chengdu-Chongqing	Chongqing	6.1301	6.6294	4.9520	12.3191	19.3580	0.0029	0.0021	12.1555	10.0245	20.7558
	Chengdu	1.6437	4.1895	1.4816	1.0140	2.2115	3.8876	4.5320	4.5141	4.7918	4.9951
Beijing-Tianjin – Hebei	Beijing	27.9890	18.6702	20.3055	21.3808	22.7380	11.1004	11.8468	11.5538	11.9604	16.4947
	Tianjin	0.0026	0.0027	0.0028	2.6379	0.0029	0.8424	2.2862	2.9349	5.3392	5.4317
Yangtze River	Shanghai	9.9146	10.2049	10.9814	11.6372	12.1600	4.6948	5.0640	5.1813	5.2005	6.1190

Delta	Hangzhou	2.3739	3.7797	2.0742	4.3307	3.9559	3.9205	4.4872	4.6155	5.0706	5.5610
Guangdong, Hong Kong and Macao Greater Bay Area	Guangzhou	1.4015	1.6679	2.2523	2.4478	2.5343	6.5901	7.1213	7.8226	7.6441	8.9401
	Shenzhen	0.6537	1.8650	0.8832	0.9782	1.5773	2.6519	2.9698	3.2620	3.4817	3.5054

(Note: Due to space constraints and the significant variance in spatial interaction strength between Luoyang and Nanyang and the cities in the four world-class airport clusters, this paper only includes the top two cities.)

Source: By authors.

Table 4 Evaluation results of spatial interaction intensity between Xinyang and the world-class airport cluster cities

Year/world-class airport cluster cities	Yangtze River Delta		Chengdu-Chongqing		Beijing-Tianjin - Hebei		Guangdong, Hong Kong and Macao Greater Bay Area	
	Shanghai	Hangzhou	Chongqing	Chengdu	Beijing	Tianjin	Foshan	Shenzhen
2018	1.4985	1.1446	2.1666	0.0021	1.0339	0.0019	0.3915	0.0010
2019	9.0925	6.8802	13.0785	2.8016	6.1953	0.3531	2.1569	0.0022

(Note: Due to space constraints and the significant variance in spatial interaction strength between Luoyang and Nanyang and the cities in the four world-class airport clusters, this paper only includes the top two cities.)

Source: By authors.

According to the results of Table 3 and Table 4, the spatial interaction intensity between Luoyang, Nanyang and Xinyang and the cities within the world-class airport clusters shows a trend of "weak vertical growth" and "horizontal polarization". Specifically, Luoyang, Nanyang and Xinyang are utilizing air transportation to leverage the economic radiation-driven role of the four world-class airport cluster cities, albeit at a relatively low total amount. For example, the spatial interaction strength between Luoyang, Nanyang and Xinyang with Chongqing increased respectively from 6.1301, 0.0029, 2.1666 in 2015 to 19.3580, 20.7558, and 13.0785 in 2019. The overall growth rate is modestand the growth prospect is weak. Additionally, the phenomenon of "horizontal polarization" is evident: the spatial interaction strength between Luoyang, Nanyang, and Xinyang with the world-class airport cluster cities is facing a "polarization" problem. For instance, in 2019, the spatial interaction strength between Luoyang and Chongqing reached 19.3580, whereas the corresponding figure for Chengdu was merely 2.2115. The gap between these two values is significant, indicating substantial polarization.

4 Conclusions and Policy Suggestions

This paper measures the spatial interaction strength between Henan's airport cities and cities in the four world-class airport clusters in China from 2015 to 2019 adopting an improved gravity model based on flight frequency. The empirical results show that:

(1) The spatial interaction strength between Zhengzhou and cities in the four world-class airport clusters features "consistent vertical enhancement and horizontal polarization".

(2) The spatial interaction intensity between Zhengzhou and the cities in the four world-class airport clusters demonstrates a "hierarchical differentiated pattern." Specifically, , with regards to the Yangtze River Delta airport cluster, Chengdu-Chongqing airport cluster, Guangdong-Hong Kong-Macao Greater Bay Area airport cluster, and Beijing-Tianjin-Hebei airport cluster, the interaction intensity follows distinct patterns:

- Yangtze River Delta airport cluster: Characterized by "one core, one main, and multiple points" pattern.
- Chengdu-Chongqing airport cluster: Exhibits a "one core, one sub-scattered point" pattern.
- Guangdong-Hong Kong-Macao Greater Bay Area airport cluster: Displays "dual cores with scattered differentiation."
- Beijing-Tianjin-Hebei airport cluster: Shows "one core with scattered differentiation."

(3) The spatial interaction intensity between Luoyang, Nanyang and Xinyang with cities in the four world-class airport clusters shows the trend of "weak vertical growth and horizontal polarization".

Drawing from the aforementioned empirical research and data analysis and aligning with the new situation and trend of China's high-quality economic development, as well as considering the actual economic landscape in Henan Province, we present the following countermeasures and suggestions for optimizing Henan's air route network. Additionally, we explore ways to leverage the comparative advantages of air transportation to capitalize on the radiation and driving effect of the Yangtze River Delta and other pivotal regions that serve as the "power source" for high-quality economic development. These proposed measures aim to foster local economic development in a manner that aligns with high-quality standards.

Firstly, Henan should fully utilize the air transportation industry to strengthen its economic connections with the four world-class airport clusters and maximize the radiation and driving effect of the Yangtze River Delta and other "power sources". As an important channel for Henan to integrate into the "power source" areas of China's high-quality economic development such as the Yangtze River Delta, Henan should bolster its air transportation market ties with the four world-class airport clusters, continue to consolidate and deepen the strength of air transportation ties with the Yangtze River Delta Airport Cluster and the Chengdu-Chongqing Airport Cluster, and gradually strengthen its air transportation ties with the Guangdong-Hong Kong-Macao Greater Bay Area Airport Cluster and the Beijing-Tianjin-Hebei Airport Cluster. Concurrently, Henan Province should escalate investment in airport infrastructure, enhance the operational capacity and service level of airports, with the goal of closing the gap with world-class airport cluster cities.

Secondly, Zhengzhou, Luoyang, Nanyang, and Xinyang should strategically differentiate and enhance the construction of their air transportation networks in collaboration with the four world-class airport clusters. Zhengzhou should leverage its geographical advantages to establish a comprehensive "north-south, east-west" route network. It should prioritize strengthening air transportation market connections with core hubs in the four world-class airport clusters, including Shanghai, Hangzhou, Chongqing, Chengdu, Guangzhou, Shenzhen, Beijing, and others. This strategic approach aims to position Zhengzhou as the pivotal platform for realizing collaboration among the four world-class airport clusters. The "power source" cities empower the high-quality economic development of Henan Province. Concurrently, efforts should be made to further optimize Zhengzhou's route network, increase flight frequencies with the Yangtze River Delta Airport Group and Chengdu-Chongqing Airport Group, expand the route network with the Guangdong-Hong Kong-Macao Greater Bay Area, Beijing-Tianjin-Hebei, and other regions, aiming to form a diversified and multi-tiered air transportation pattern. Luoyang and Nanyang should focus on strengthening air transportation links with the Chengdu-Chongqing airport cluster and the Beijing-Tianjin-Hebei airport cluster, as well as strengthening air transportation links with Chongqing, Beijing, Shanghai and Guangzhou. Xinyang should focus on strengthening air transportation connections with the Yangtze River Delta airport cluster and Chengdu-Chongqing airport cluster, and on strengthening air transportation channels with Shanghai, Chongqing and Beijing.

Thirdly, promotion of centralized and unified management of provincial airports is essential for Henan to achieve a "trunk and branch" model for linked development. Henan should overcome barriers hindering synergistic development due to the distinct property rights of the four aforementioned airports to achieve centralized and unified management of the airports in Henan, ensuring that the Zhengzhou aviation hub capitalizes on its advantage within the network of extra-provincial routes. The strategy involves driving operational excellence for feeder airports like Luoyang, Nanyang, and Xinyang through the principles of "unified standards, unified operation, and unified development." This concerted effort aims to expedite Henan's integration into China's modern economic system, fostering high-quality economic development. In addition, the "trunk and branch linkage, synergistic development" model helps to speed up the integration of Henan into the national modern economic system and achieve the high-quality economic development.

This study has innovatively constructed an enhanced gravity model, based on flight frequency, and incorporating differences in airport passenger flow, to underscore the pivotal role of air transportation more objectively in promoting spatial interactions. However, the study has certain limitations concerning sample selection, the time span of the sample, and the design of the gravity model. Future research should concentrate on varying research subjects, while simultaneously expanding the sample time span and introducing additional analytical indicators. This would help to comprehensively depict the complexity of air transportation and further investigate the relationship between the strength of spatial interactions among regions.

Acknowledgements

We are grateful for the financial support from the National Natural Science Foundation of China (U2333206); the Major Project of Key Research Base of Humanities and Social Sciences of the Ministry of Education of China (22JJD630006); the Civil Aviation Safety Capacity Building Project of 2024 "Domestic Air Express Safety Supervision"; and the Major Project of Social Sciences of Tianjin Municipal Commission of Education (2018JWZD52).

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