ISSN 2706-6827 Vol. 8, Issue 3: 20-26, DOI: 10.25236/IJFS.2026.080304

Multi-flow Coordination and Core-city Siphoning in Guangdong's Metropolitan Areas

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Abstract: *Metropolitan areas are expected to improve regional integration by facilitating the circulation of people, information, transport services, and economic resources. In practice, however, different flows may not move in the same direction, and the concentration of population and resources in core cities can weaken internal coordination. Taking Guangdong Province as a case, this study examines five metropolitan areas through four types of intercity flow data: transport flow, information flow, population flow, and economic flow. Social network analysis and QAP correlation analysis are used to identify the degree of coordination among flow networks and the relative position of cities within each metropolitan area. The results show that transport, information, and economic flows are strongly associated, whereas population flow is weakly correlated with the other networks. Guangzhou and Shenzhen show strong centrality across all four flow dimensions, while the core-city roles of Zhuhai, Shantou, and Zhanjiang are less stable. These findings suggest that Guangdong's metropolitan development is marked by both network integration and uneven core-periphery relations. The study contributes a compact multi-flow framework for evaluating metropolitan coordination and offers policy implications for improving core-city spillovers, supporting secondary metropolitan areas, and promoting more balanced population mobility.*

Keywords: *Guangdong metropolitan areas; multi-dimensional flow elements; social network analysis; siphoning effect; multi-flow coordination*

1. Introduction

Regional coordination has become a central concern in urban and regional studies. The OECD has emphasized that regional disparities and uneven access to development opportunities remain major challenges for both cities and rural regions [1]. As economies become increasingly connected through infrastructure, digital platforms, labour mobility, and intercity economic exchange, regional development can no longer be understood only through administrative boundaries or static economic indicators. Metropolitan areas are especially important in this context because they function as spatial units in which nearby cities are expected to share infrastructure, coordinate industrial functions, and improve the circulation of production factors [2,3].

The concept of the space of flows provides a useful theoretical lens for this issue. Castells argued that contemporary spatial organization is shaped not only by places but also by flows of information, people, capital, and goods [4]. This perspective has been widely applied in urban network studies, which examine how cities are connected through relational data rather than only through geographical proximity. Existing studies have used transport, information, migration, innovation, and economic flows to identify urban hierarchy, regional integration, and functional division of labour [5-7]. However, many studies focus on a single type of flow or treat different flows as naturally coordinated. In reality, transport, information, economic, and population flows may produce different network patterns. A city may be central in the economic network but peripheral in population mobility, or it may attract people without generating proportional spillover effects for neighbouring cities.

Core-city siphoning is closely related to this problem. In metropolitan development, core cities usually have stronger employment opportunities, public services, higher-order industries, and innovation resources. These advantages can generate positive spillovers, but they can also intensify the concentration of people and resources. When population and talent move predominantly toward the core city, secondary and peripheral cities may find it difficult to build their own development momentum. The relationship between multi-flow coordination and core-city siphoning therefore deserves closer empirical attention.

Guangdong Province provides a suitable case for this analysis. It is one of China's most

ISSN 2706-6827 Vol. 8, Issue 3: 20-26, DOI: 10.25236/IJFS.2026.080304

economically dynamic provinces, but its internal development remains uneven. The Pearl River Delta contains highly developed cities such as Guangzhou and Shenzhen, while eastern and western Guangdong still face weaker infrastructure, smaller economic scale, and lower factor attraction. In recent provincial planning, Guangdong has promoted a metropolitan structure consisting of the Guangzhou, Shenzhen, Pearl River West Bank, Shantou-Chaozhou-Jieyang, and Zhanjiang-Maoming metropolitan areas [8,9]. These areas are expected to support more coordinated provincial development, yet their internal network structures and core-city capacities differ considerably.

This study asks three questions. First, to what extent are transport, information, population, and economic flows coordinated across Guangdong's metropolitan areas? Second, which cities occupy central positions in each flow network? Third, how does the pattern of population flow relate to the siphoning role of core cities? To answer these questions, the study constructs four intercity flow networks and applies social network analysis and QAP correlation analysis. Social network analysis is suitable for examining relations among actors and flows through those relations [10,11].

2. Study Area, Data, and Methods

2.1 Study Area

The empirical analysis focuses on Guangdong's five metropolitan areas at the prefecture-city scale. The Guangzhou metropolitan area includes Guangzhou, Foshan, Zhaoqing, and Qingyuan. The Shenzhen metropolitan area includes Shenzhen, Dongguan, and Huizhou. The Pearl River West Bank metropolitan area is examined through Zhuhai, Zhongshan, Jiangmen, and Yangjiang. The Shantou-Chaozhou-Jieyang metropolitan area includes Shantou, Chaozhou, and Jieyang, while the Zhanjiang-Maoming metropolitan area includes Zhanjiang and Maoming. Because the networks are constructed at the prefecture-city level, some sub-municipal planning units and special cooperation zones are not included. The cities included in each metropolitan area are listed in Table 1.

Table 1. Metropolitan areas and cities included in the study

Metropolitan area	Cities included in the empirical analysis	Main core city in planning and policy discourse
Guangzhou	Guangzhou, Foshan, Zhaoqing, Qingyuan	Guangzhou
Shenzhen	Shenzhen, Dongguan, Huizhou	Shenzhen
Pearl River West Bank	Zhuhai, Zhongshan, Jiangmen, Yangjiang	Zhuhai
Shantou-Chaozhou-Jieyang	Shantou, Chaozhou, Jieyang	Shantou
Zhanjiang-Maoming	Zhanjiang, Maoming	Zhanjiang

2.2 Data Sources

Four types of flow data are used to construct intercity networks. Transport flow is measured by the number of road and rail passenger services between city pairs. The road passenger data are collected from Guangdong Transport, LY.com, and Trip.com, while rail passenger data are collected from the official 12306 railway platform. To reduce holiday bias, the study uses one regular working week in December 2024 and calculates intercity service frequency.

Information flow is measured with Baidu Index and Ocean Engine Index data. The indicators include Baidu search attention, Baidu news attention, and the Ocean Engine keyword composite index. City names are used as keywords, and the annual daily average for 2024 is used to reduce the influence of short-term news events. Baidu Index has been widely used in studies of intercity information linkages [12].

Population flow is derived from Baidu Migration data from December 2024 to January 2025. The data include intercity migration proportions by origin and destination. Because this period overlaps with the Spring Festival travel season, the results are interpreted as evidence of concentrated mobility patterns rather than as a complete measure of annual population redistribution. Previous research has shown how the Baidu Migration Scale Index can be converted into estimated migration volume [13]. Economic flow is estimated from GDP, population, urbanization rate, and road distance. GDP and population indicators are taken from the Guangdong Statistical Yearbook 2024, and intercity road distances are obtained from Amap.

ISSN 2706-6827 Vol. 8, Issue 3: 20-26, DOI: 10.25236/IJFS.2026.080304

2.3 Network Construction

Transport linkage strength is calculated as:

$$Tij = Hij + Rij$$

where H_{ij} denotes the number of road passenger services between cities i and j, R_{ij} denotes the number of rail passenger services, and T_{ij} denotes overall transport linkage strength.

Information linkage strength is calculated by combining Baidu Index and Ocean Engine Index linkages. Following existing studies on intercity association measurement [12,14], the linkage between two cities is estimated through the product of two-way attention values:

$$M=M_{bi}\times M_{bj}+M_{ti}\times M_{tj}$$

where M denotes information-flow strength between cities i and j; M_{bi} and M_{bj} denote the two-way Baidu Index attention values; and M_{ti} and M_{tj} denote the corresponding Ocean Engine Index values.

Population linkage strength is calculated as:

$$P = Pij + Pji$$

where P_{ij} and P_{ji} denote migration volumes in the two directions between cities i and j. Following previous work on Baidu Migration data [13], the migration scale index M^t_i *and actual migration volume* H^t_i are assumed to satisfy a simple linear relationship:

$$M^t_{i*} = kH^t_{i*}, \quad k=3.24\times 10^{-5}$$

Economic linkage is measured with a modified gravity model, which is commonly used to estimate spatial economic interaction between cities [15]:

$$R_{ij}=K_{ij}\frac{\sqrt{P_iG_i}\sqrt{P_jG_j}}{D_{ij}^2}$$

where $K_{ij} = U_i / U_j$; U_i and U_j are the urbanization levels of cities i and j; P_i and P_j are permanent resident populations; G_i and G_j are GDP; and D_{ij} is the shortest road distance between the two cities.

2.4 Analytical Methods

The study uses two main methods. First, QAP correlation analysis is applied to examine whether different flow networks are associated with one another. Before QAP analysis, the matrices are binarized using natural-break thresholds: 210 for transport flow, 15,574.5 for information flow, 208.43 for population flow, and 4,043.33 for economic flow. Values equal to or above the threshold are coded as 1, and values below the threshold are coded as 0.

Second, weighted degree centrality is used to identify the relative position of each city in the flow networks. For node i, weighted degree centrality is calculated as:

$$C_{di}^{w} = \sum\nolimits_{j\in \mathrm{neighbors}(i)} \mathrm{weight}\,(i,j) + \sum\nolimits_{j\in \mathrm{predecessors}(i)} \mathrm{weight}\,(j,i)$$

where neighbors(i) denotes the set of outgoing neighbouring nodes of node i, predecessors(i) denotes the set of incoming predecessor nodes of node i, weight(i,j) denotes the weight of the edge from i to j, and weight(j,i) denotes the weight of the edge from j to i. The results are normalized within each metropolitan network, so they indicate relative centrality rather than absolute inter-metropolitan scale.

3. Results

3.1 Coordination among Flow Networks

The QAP correlation results are reported in Table 2. The QAP results show a clear contrast between population flow and the other three flow networks. Economic flow and information flow are strongly correlated, with a coefficient of 0.813. Transport flow and information flow also show a strong correlation, with a coefficient of 0.829. Economic flow and transport flow are positively associated as well, with a coefficient of 0.605. These results indicate that cities with stronger economic and transport linkages tend to have more active information exchange.

ISSN 2706-6827 Vol. 8, Issue 3: 20-26, DOI: 10.25236/IJFS.2026.080304

Population flow differs from this pattern. Its correlations with economic flow and information flow are slightly negative and statistically insignificant. Its correlation with transport flow is positive but weak, with a coefficient of 0.188 and a p-value of 0.098. This means that population mobility is not closely aligned with the transport, information, and economic networks in the current dataset. The result should not be interpreted as direct proof of siphoning, but it is consistent with a siphoning pattern in which population movement is more strongly concentrated toward core cities than distributed across the metropolitan network.

Table 2. QAP correlations among flow networks

Flow pair	Correlation coefficient	p-value	Interpretation
Economic flow - Information flow	0.813	0.000	Strong positive association
Transport flow - Information flow	0.829	0.000	Strong positive association
Economic flow - Transport flow	0.605	0.001	Moderate to strong positive association
Population flow - Transport flow	0.188	0.098	Weak positive association
Population flow - Economic flow	-0.017	0.934	No significant association
Population flow - Information flow	-0.021	0.903	No significant association

The weak association between population flow and the other flows is particularly relevant for Guangzhou and Shenzhen. During the observation period, Guangzhou accounted for about 57% of total migration in the Guangzhou metropolitan area, while Zhaoqing and Qingyuan accounted for much smaller shares. Shenzhen accounted for about 50% of migration in the Shenzhen metropolitan area. These figures suggest that population movement is strongly oriented toward the leading cities. Such concentration may help core cities maintain their economic vitality, but it may also make it harder for surrounding cities to transform transport and economic linkages into balanced regional development.

3.2 Centrality and Metropolitan Differentiation

Table 3 presents the normalized weighted degree centrality of cities in the four flow networks. The centrality results confirm the uneven structure of Guangdong's metropolitan areas. Guangzhou and Shenzhen are the only cities that rank highest across all four flow dimensions in their respective metropolitan areas. This indicates that they are not only administrative or economic centres but also central nodes in transport, information, population, and economic networks.

Table 3. Weighted degree centrality of cities in four flow networks

Metropolitan area	City	Transport	Information	Population	Economic
Guangzhou	Guangzhou	1.00	1.00	1.00	1.00
Guangzhou	Foshan	0.61	0.83	0.59	0.95
Guangzhou	Zhaoqing	0.59	0.20	0.43	0.06
Guangzhou	Qingyuan	0.36	0.22	0.94	0.07
Pearl River West Bank	Zhuhai	1.00	1.00	1.00	0.64
Pearl River West Bank	Zhongshan	0.84	0.95	0.79	1.00
Pearl River West Bank	Jiangmen	0.60	0.73	0.41	0.70
Pearl River West Bank	Yangjiang	0.57	0.38	0.09	0.09
Shantou-Chaozhou-Jieyang	Shantou	1.00	1.00	1.00	0.69
Shantou-	Chaozhou	0.92	0.81	0.61	0.65

ISSN 2706-6827 Vol. 8, Issue 3: 20-26, DOI: 10.25236/IJFS.2026.080304

Chaozhou-Jieyang					
Shantou-Chaozhou-Jieyang	Jieyang	0.89	0.71	0.67	1.00
Shenzhen	Shenzhen	1.00	1.00	1.00	1.00
Shenzhen	Dongguan	0.78	0.83	0.77	0.80
Shenzhen	Huizhou	0.41	0.47	0.78	0.53
Zhanjiang-Maoming	Zhanjiang	1.00	1.00	1.00	1.00
Zhanjiang-Maoming	Maoming	1.00	1.00	1.00	1.00

In the Guangzhou metropolitan area, Guangzhou is the dominant node in all four networks, but Foshan is also highly connected, especially in information and economic flows. Zhaoqing and Qingyuan are much weaker in the economic network, with centrality values of 0.06 and 0.07. This indicates that the Guangzhou-Foshan connection is strong, while the wider metropolitan area remains uneven. Qingyuan's high population centrality should be interpreted cautiously because the migration data capture a specific period of large-scale seasonal mobility.

The Shenzhen metropolitan area shows a more integrated structure. Shenzhen remains the leading node, but Dongguan has relatively high centrality in all four dimensions. Huizhou is weaker in transport and information flows, although its population-flow centrality is not low. Compared with Guangzhou, the Shenzhen metropolitan area appears more compact, with stronger linkages between the core city and its neighbouring manufacturing cities.

The Pearl River West Bank metropolitan area presents a less stable core structure. Zhuhai ranks first in transport, information, and population flows, but Zhongshan has the highest economic-flow centrality. Jiangmen occupies an intermediate position, while Yangjiang is weak in information, population, and economic flows. This suggests that the designated core city does not fully dominate the metropolitan network and that the area has a more fragmented internal structure.

The Shantou-Chaozhou-Jieyang metropolitan area is relatively balanced, but this balance is partly associated with a lower overall development level. Shantou ranks first in transport, information, and population flows, but Jieyang is stronger in economic flow. Chaozhou has relatively close linkages but does not dominate any dimension. The area therefore shows internal proximity without a strong growth pole.

The Zhanjiang-Maoming metropolitan area is difficult to interpret with centrality measures because it contains only two cities. Both cities receive identical normalized scores. This does not mean that the two cities have the same development level; rather, it reflects the limitations of measuring centrality in a two-node network. For this reason, policy interpretation should rely more on substantive economic and infrastructural conditions than on the normalized centrality value alone.

4. Discussion

The findings suggest that metropolitan coordination should be understood as a multi-flow process. Transport, information, and economic flows in Guangdong are strongly related, which means that infrastructure, market interaction, and information exchange tend to reinforce one another. Population flow, however, follows a different logic. Its weak association with the other networks indicates that mobility is shaped not only by intercity connectivity but also by the attraction of employment, public services, housing markets, and urban opportunities in the core cities.

This distinction matters for evaluating core-city siphoning. Guangzhou and Shenzhen are central across all four networks, and their population attraction is especially strong. Their dominance can create positive spillovers, but if population and talent remain concentrated in the core cities, surrounding cities may not fully benefit from transport and economic integration. This is particularly evident in the Guangzhou metropolitan area, where Guangzhou and Foshan are closely connected while Zhaoqing and Qingyuan remain weak in economic centrality. In the Pearl River West Bank metropolitan area, the problem is different: the core city does not have enough comprehensive centrality to coordinate the whole network, and economic activity is more strongly associated with Zhongshan.

The results also show why a separate core-periphery analysis is not necessary in the shortened

ISSN 2706-6827 Vol. 8, Issue 3: 20-26, DOI: 10.25236/IJFS.2026.080304

version of the paper. In small metropolitan networks with two to four cities, core-periphery classification largely repeats the information already provided by centrality. The key empirical issue is not whether a city can be labelled core or peripheral, but whether the same city remains central across transport, information, population, and economic flows. A multi-flow centrality approach therefore provides a more concise way to identify metropolitan imbalance.

From a policy perspective, Guangdong's metropolitan areas require differentiated strategies. For Guangzhou and Shenzhen, the priority is not only to strengthen the core cities but also to improve their spillover capacity. Industrial cooperation, public-service sharing, and infrastructure coordination should be directed toward surrounding cities rather than concentrated within the core. For the Pearl River West Bank metropolitan area, coordination should focus on clarifying the functional relationship among Zhuhai, Zhongshan, Jiangmen, and Yangjiang. Zhuhai needs stronger economic coordination capacity, while Zhongshan's economic role should be better integrated into the metropolitan framework. For Shantou-Chaozhou-Jieyang and Zhanjiang-Maoming, basic connectivity, industrial upgrading, and public-service integration remain more important than the pursuit of a strong hierarchical network.

Population policy is also important. Instead of relying only on talent attraction by core cities, metropolitan areas need mechanisms that support more balanced mobility. Housing support, employment services, education and healthcare access, and targeted incentives can make secondary and peripheral cities more attractive to young workers and skilled labour. Digital information platforms may also reduce information asymmetry by making jobs, public services, and business opportunities in non-core cities more visible.

5. Conclusion

This study examines multi-flow coordination and core-city siphoning in Guangdong's five metropolitan areas. By constructing transport, information, population, and economic networks, it shows that transport, information, and economic flows are strongly coordinated, while population flow is weakly associated with the other three networks. This finding suggests that population mobility does not automatically follow the pattern of infrastructure and economic linkages. Instead, it is more strongly shaped by the attraction of core cities.

The centrality analysis further reveals differentiated metropolitan structures. Guangzhou and Shenzhen are strong comprehensive cores. Foshan and Dongguan also play important supporting roles, but Zhaoqing, Qingyuan, Huizhou, Yangjiang, and other peripheral cities remain less integrated in some flow dimensions. The Pearl River West Bank metropolitan area has a fragmented structure in which Zhuhai's core role is incomplete and Zhongshan has strong economic centrality. The Shantou-Chaozhou-Jieyang and Zhanjiang-Maoming areas are relatively balanced internally but have weaker overall development momentum.

The study provides a compact framework for evaluating metropolitan coordination through multiple flows. It also shows that core-city siphoning should be analyzed cautiously: weak population-flow coordination does not by itself prove siphoning, but it can reveal whether population mobility is aligned with broader metropolitan integration. Future research should use longer time-series mobility data, finer spatial units, and additional indicators such as commuting, firm linkages, and public-service accessibility to test the robustness of these findings.

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