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Spatial relationship of high-speed transportation construction and land-use efficiency and its mechanism:

Case study of Shandong Peninsula urban agglomeration

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Abstract: Land-use efficiency is low for the urban agglomeration of China. High-speed transportation construction has been an important factor driving land use change. It is critically important to explore the spatial relationship between the high-speed transportation superiority degree and land-use efficiency. We built a model to evaluate the benefits of convenient high-speed transportation using the relative density of highways and the distance from high-speed rail stations and airports as a metric. We used 42 counties of the Shandong Peninsula urban agglomeration as an example. Land-use efficiency was calculated by a DEA model with capital, labor, economic benefits and environmental benefits as input and output factors. We examined the spatial relationships between high-speed transport superiority degree and land-use efficiency and obtained the following results. First, there are significant spatial differences in the relationships between the high-speed transportation superiority degree and land-use efficiency. Taking the two major cities of Jinan and Qingdao as the hubs, the core surrounding counties show significant spatial relationship between land-use efficiency and the high-speed transportation superiority degree. Spatial correlation declines as the distance from the hubs increases. Land-use efficiency is less than high-speed transportation convenience in areas along the transportation trunks that are distant from the hub cities. Correlation is low in areas that are away from both hub cities and transportation trunk routes. Second, high-speed transportation has a positive relationship with land-use efficiency due to the mechanism of element agglomeration exogenous growth. Third, high-speed transportation facilitates the flow of goods, services and technologies between core cities and peripheral cities as space spillover (the hub effect). This alters the spatial pattern of regional land-use efficiency. Finally, the short-board effect caused by decreased high-speed transport construction can be balanced by highway construction and the proper node layouts of high-speed rail stations and airports, resulting in a well-balanced spatial pattern of land-use efficiency.

Keywords: high-speed transportation superiority degree; DEA; land-use efficiency; spatial relationship; Shandong Peninsula urban agglomeration

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1 Introduction

During China's rapid urbanization, many serious urban land use problems arose, such as the unconstrained scale of development, uncontrolled land use, imbalanced structural distribution, and environmental degradation (Liu *et al.*, 2008; Wu *et al.*, 2018). For example, the average annual increase in China's urban construction land use was 1.09% between 2005 and 2014. In comparison with this sustained urban construction, the value-added growth of China's secondary and tertiary industries decreased annually by 0.4% on average over the same period. Thus, in the last 10 years, China's large-scale land development and construction have not increased income; on the contrary, they have wasted or even destroyed valuable land resources (Xu *et al.*, 2009; Du, 2016). These conditions show a need not only to manage total land use but also to improve land use quality. We should focus on intensive land use and input-output analysis.

Land-use efficiency is a typical measure of the intensity of land use and is used to evaluate inputs and outputs (Chen *et al.*, 2016). The Western ecological approach primarily involves land-use efficiency, and it includes descriptions and inference of land use. The approach examines urban land use with four types of models: transect models, concentric models, sector models, and multiple nuclei (core) models (Johnson, 1960; Chapin and Kaiser, 1967; Liu *et al.*, 2001). In contrast, domestic Chinese scholars have studied basic urban land-use efficiency and have developed different practical methods of evaluation, such as principal component analysis (Li *et al.*, 2005), regression analysis (Liu *et al.*, 2005), synergy (Ou *et al.*, 2007), fuzzy comprehensive assessment (Jia and Hao, 2011), data envelopment analysis (Wu *et al.*, 2011), the analytic hierarchy process (Guan and Chen, 2013), and the SBM-Undesirable model (Yang *et al.*, 2014). In these studies, the impacts of economic development, policy, industry, and consumption patterns on urban land use are identified (Peneder, 2003; Lambin and Geist, 2003; Defries *et al.*, 2004; Akkemik, 2005).

Transportation is an important driving factor in land use change (Wang *et al.*, 2015; Ma *et al.*, 2018). It affects the form of urban space (Wang *et al.*, 2008), land use structure (Cervero and Kang, 2011), and land prices (Gu and Zheng, 2010; Debrezion *et al.*, 2011). The relationship between transportation and land use can be explained by a combination of models (Guo *et al.*, 2015). Most research focuses on the relationship between land use and transportation systems within a single city. There are few studies of regionally integrated transportation systems and overall land use patterns. In recent years, China's urban agglomerations have been extensively developed, and their input-output efficiency is low (Fang and Guan, 2011; Wang *et al.*, 2014). The introduction of high-speed rail and other high-speed transportation modes makes it important to study their influence on land-use efficiency. To investigate these issues and identify the relationship between high-speed transportation and land-use efficiency, we use the Shandong Peninsula urban agglomeration as a case study and develop a method to evaluate the degree of superiority for a system of high-speed transportation.

2 Study area and data

2.1 Study area

The study area is the Shandong Peninsula urban agglomeration on the eastern coast of China.

It includes Jinan, Qingdao, Zibo, Dongying, Yantai, Weifang, Weihai, Rizhao, and Zouping. The rapidly-developing transportation system has created a high-speed network of highways, high-speed railways and air transport which has given the urban agglomeration a significant competitive advantage. In 2014, there were 2782 km of highway in the Shandong Peninsula with a highway density of 0.037 km/km^2, which is 3.1 times the national level. There are three major high-speed rail lines (the Jing-Hu line Shandong section, the Jiao-Ji line and the Qing-Yan-Wei-Rong line), six transport airports (Jinan, Qingdao, Dongying (Kenli), Yantai, Weifang and Weihai) and four general aviation airports (Xueye, Penglai, Dagao and Pingyin). The two major transportation centers of Jinan and Qingdao have become interregional high-speed transportation hubs.

2.2 Data

The study period was 2014, and the basic unit of evaluation is the county. The islands around the peninsula have no high-speed transport facilities, so the 42 land-based county-level units (counties, county-level municipalities or municipal districts) are the units of evaluation. Highway distance data for 2014 were provided by the Shandong Provincial Communications Planning and Design Institute. Six civil transportation airports (Jinan, Qingdao, Dongying, Yantai, Weifang and Weihai) and 16 high-speed rail stations (one representative station was selected for each county: Jinan West, Qingdao, Jiaozhou North, Jimo North, Laixi North, Zibo, Yantai South, Laiyang, Haiyang North, Weifang, Qingzhou, Gaomi, Changle, Weihai and Rongcheng) were selected. High-speed rail stations were selected according to the following principles: official stations have precedence over informal stations; informal stations are selected by frequency of use; and stations are selected randomly. For convenience and simplicity, the town-level stations along the Qing-Yan-Wei-Rong line are not included in the samples. Most of the stations identified only link with other stations along the line and lack interregional connections. Being close to an intercity connection is less distanct than to interregional connection, so the overall external strength of intercity nodes is inadequate. Land input and output data were obtained from the Shandong Province Urbanization Development Report (2015) and Shandong Statistical Yearbook (2015).

3 Methods

3.1 Evaluation of high-speed transportation superiority degree

The *transportation superiority degree*, which is a comprehensive index for regional transportation support, contact, agglomeration, and locational advantage, was first proposed by Jin *et al*. (2008). Taking a large-scale regional system, including the area to be evaluated, as the network object, transportation level and grade are quantified by analysis and comparison. To obtain the relative advantage of a single transportation mode, the high-speed transportation superiority degree is used to enumerate the advantages of regional high-speed transportation. The evaluation of high-speed transportation superiority uses a quantitative comparison model to evaluate the regional high-speed transportation level and grade, which includes the high-speed transportation network, density, and axial radiation. Then, transportation superiority is determined as follows (Jin *et al*., 2008; Wang *et al*., 2010; Meng *et al*., 2014).

(1) Calculate the density of the transportation network. If A_i is the administrative area and

L_i is the length of the transportation links or the number of nodes, transportation network density, then $D_i=L_i/A_i$.

(2) Evaluate the impact of transportation links and nodes (hubs) on the area. First, determine if there are transportation links and nodes (facilities) in the area. If there are not, then calculate the distance between the area and the closest transportation links and nodes. Then determine the impact value according to transportation type and distance.

(3) Evaluate regional superiority. Rank the distances between each area and the central city of the region, and then assign a value to each ranked item.

This framework allows the development of a simple and practical evaluation of high-speed transportation superiority. High-speed transportation has three major subsystems, i.e., highways, high-speed rail, and air transport. The superiority of each subsystem can be adjusted as follows.

(1) As highways have multiple entrances and are continuous and narrow, calculate their superiority by the highway network density (i.e., the ratio of highway distance to area).

(2) The station is the main point of impact of high-speed rail, so calculate its superiority at any point by observing its distance from the station, choosing 30 km and 60 km as base distance units (Jin *et al*., 2008).

(3) The superiority index for air transport superiority is similar to that of high-speed rail, but in order to highlight the difference, airports are divided into two important airports, Jinan and Qingdao, and four ordinary airports, Dongying, Yantai, Weifang and Weihai.

Each subsystem is given a weight of 1/3, and high-speed transport superiority is equal to the sum of the products of the score and the weight. Weight apportionments are given in Table 1.

Table 1 Evaluation of high-speed transportation superiority degree

Evaluation system	Evaluation subsystem	Score
High-speed transport superiority degree	Highway superiority degree	• The ratio of regional highway density to that of urban agglomeration
	High-speed railway superiority degree	• Has high-speed rail station (score 2)
		• Within 30 km from the high-speed rail station (score 1.5)
		• 30-60 km away from high-speed rail station (score 1)
	Air transport superiority degree	• Has important airport (score 2)
		• Has ordinary airport (score 1.5)
		• Within 50 km of the important airport (score 1) or ordinary airport (score 0.5)

3.2 Data envelopment analysis

3.2.1 Introduction

Data envelopment analysis (DEA) is a nonparametric linear programming method (Charnes *et al*., 1978; Banker *et al*., 1989). DEA uses relative efficiency to evaluate multiple inputs and outputs for decision-making units, and it avoids the subjectivity and computational overhead of parameter estimation (Li and Chen, 2003). There are five major DEA models: CCR, BCC, CCGSS, CCW and CCWH. As a measurement method in terms of constant return to scale, CCR is suitable for the evaluation of indicator validity and contribution rate, so it is an effective tool to evaluate land-use efficiency (Yu, 2002). An assumption of DEA is that the study object includes n decision-making units (DMUs), denoted by j (j = 1, 2, …, n).

The variables for each DMU are denoted by x_j (input) and y_j (output); θ is the relative efficiency of each DMU; and λ_j is the coefficient of each linear combination of inputs and outputs. The formula for CCR is:

$$\begin{cases} \text{Min}\,\theta \\ \text{s.t.} -\sum_{j\in n} \lambda_j x_j + \theta x_0 \geqslant 0 \\ \sum_{j\in n} \lambda_j y_j \geqslant y_0 \\ \lambda_j \geqslant 0,\ j \in n \end{cases} \tag{1}$$

As aforementioned, CCR operates with constant returns to scale, and θ represents a comprehensive efficiency consisting of technical and scale efficiencies. If $\sum\lambda_j = 1$, the CCR model becomes a BCC model, and θ represents only technical efficiency.

3.2.2 Index

Land use efficiency assessment involves the economy, society, and environment (Wu *et al.*, 2011; Yang *et al.*, 2015). Because land use characteristics are for county-level units, we define land (built-up area, km^2), capital (total investment in fixed assets, yuan×1,000,000), and labor (secondary and tertiary industry employees, persons×1,000,000) as inputs. We take only economic and environmental benefits as the outputs because social benefits and technological progress are difficult to quantify. Economic benefits correspond to secondary and tertiary industry added value (billion yuan) and government revenue (million yuan), and environmental benefits correspond to the green coverage proportion of the built-up area (ha).

4 Results and analysis

4.1 High-speed transportation superiority degree

The high-speed transportation superiority index values of the 42 evaluation units are classified as follows, based on Jenks Natural Breaks Classification.

(1) Type I (1.448–2.058) includes 14.2% of the units. Type I units are mainly distributed in the eastern coastal nodes, the peninsula and inland channel junctions, and inland core areas, and mostly belong to an integrated hub and its adjacent areas.

(2) Type II (1.091–1.447) includes 19% of the units. Type II units are mainly distributed on the periphery of type I units, and show circular or scatter distributions. The type II high-speed transport combination has fewer advantages than the hub and spoke configuration of type I.

(3) Type III (0.726–1.090) includes 35.7% of the units. Type III units are mainly distributed on the peripheries of type I and type II units. They are grouped along the Jiao-Ji and Qing-Yan-Wei-Rong rail lines, and have a circle + axis layout. High-speed transportation in type III units is less influenced than type II units by the hub and spoke arrangement of type I units.

(4) Type IV (0.343–0.725) includes 23.8% of the units. Type IV units are mainly distributed in the north and south, where they are far away from the transportation trunk routes. The effect of the hubs is weak. High-speed transportation in type IV is simple as only highways are built.

(5) Type V (0–0.342) includes only Dongying, Juxian and Wulian. Of the three, only Dongying has high-speed transportation links. Because they are far away from the hubs, type V units are difficult to include in an effective high-speed transportation network.

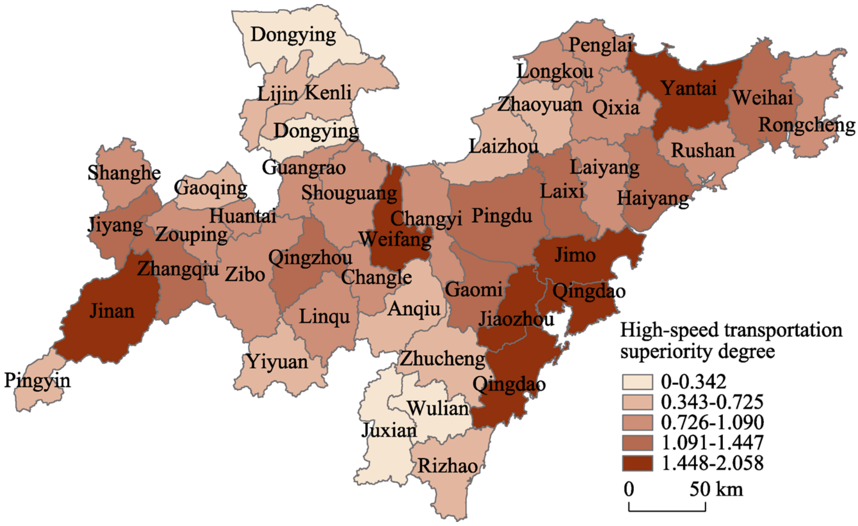

Figure 1 Spatial pattern of high-speed transportation superiority in Shandong Peninsula urban agglomeration in 2014

The type I, type II and type III units show an axis + radial spatial pattern along the Jiao-Ji and Qing-Yan-Wei-Rong lines, with Qingdao as the hub. Jinan (2.058), Weifang (1.564), Qingdao (2.038) and Yantai (1.721) are important nodes (Figure 1). Transportation routes in these areas were developed in ancient times, and the construction of highways (e.g., Ji-Qing), high-speed railways (e.g., Jing-Hu) and airports (e.g., Jinan and Qingdao) has maintained the advantage of this corridor. The status of these areas will not change in the future as more highways, high-speed railways (e.g., Ji-Qing line) and airports (e.g., Qingdao-Jiaodong and Penglai) are constructed.

A layered structure has been formed, consisting of primary (e.g., Jinan and Qingdao) and secondary groupings (e.g., Yantai-Weihai and Weifang-Qingzhou). High-speed transportation facilities radiate spatially (e.g., the airports and high-speed railway stations in Jinan and Qingdao) and affect neighboring areas. High-speed transportation superiority increases quickly in such areas, and a circular pattern, with significant spatial correlation, is seen around high-speed transportation facilities. Highways and high-speed railways are spatially continuous and are adjacent to many areas. Thus they usually constitute a complex transportation network and the high-speed transportation superiority index of the areas around high-speed transportation facilities is high because of their well-developed transportation facilities. On the whole, the above reasons led directly to the circular structure of the high-speed transportation superiority degree around hubs and nearby areas.

The superiority degree of the coastal areas (Qingdao, Yantai and Weihai) is higher than the inland areas (Jinan, Zibo, Weifang and Zouping) and is also higher than the northern (Dongying) and southern regions (Rizhao). The coastal areas have the advantage in the number of airports (3), high-speed rail land coverage (56.3%) and highway density (0.045 km/km^2), whereas the inland areas have a slightly lower superiority (2 airports, 36.8% high-speed rail land coverage, and 0.035 km/km^2 highway density). The lowest superiority values are found for Dongying, Rizhao and southern Weifang, as well as western Yantai, where there is only one airport (Dongying airport), no high-speed railway stations have been built, in some areas the density of expressways is only 0.024 km/km^2, and some areas (e.g., Juxian, Wulian and Anqiu) do not have expressways.

There is a significant positive correlation between the number of modes of high-speed transportation and superiority. We divided high-speed transportation modes into three main types (comprehensive mode: highway, high-speed railway and air transportation; portfolio mode: highway + high-speed railway; and single mode: highway) and we found that comprehensive mode (mean superiority 1.748) > portfolio mode (mean superiority 1.211) > single mode (mean superiority 0.789). In addition, the correlation between superiority and high speed railway (0.793) > the correlation between superiority and air transportation (0.779) > the correlation between superiority and highway (0.700), which is due to a relatively balanced distribution of the highway across units and the highly unequal distribution of high-speed rail and air transport across units, giving the latter two modes a larger influence on superiority.

4.2 Land-use efficiency

The land-use efficiencies of the 42 county-level units are divided into five types, based on Jenks Natural Breaks Classification and DEA, as follows.

(1) Type I (0.971–1.000) includes 33.3% of the evaluation units. Type I units generally reach optimal efficiency, and are concentrated in coastal areas of Jiaodong and inland areas with Jinan-Zibo as the core, including two central cities of Jinan and Qingdao. Most type I areas have a developed economy and a good industrial foundation or a well-developed high-tech industry.

(2) Type II (0.907–0.970) includes 28.6% of the evaluation units. Type II units are mostly concentrated on the periphery of type I units. They have different levels of economic development, due to some extent to the spatial spillover effect of land-use efficiency.

(3) Type III (0.859–0.906) includes 14.3% of the evaluation units. Type III units are mainly concentrated in the peripheries of type I and type II units, and their land-use efficiency lags behind the level of economic development in those units.

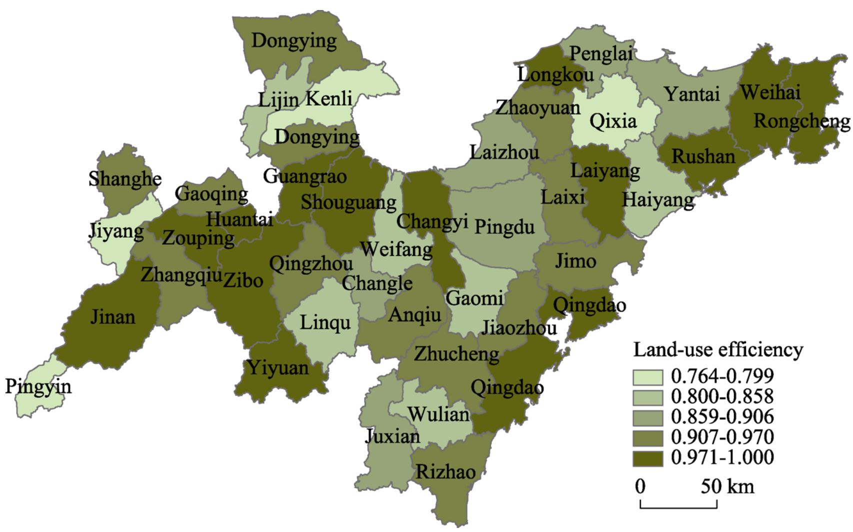

Figure 2 Spatial pattern of land-use efficiency in Shandong Peninsula urban agglomeration in 2014

(4) Type IV (0.800–0.858) includes 14.3% of the evaluation units. Type IV units have low land-use efficiency and the less developed economy shows a scattered point distribution.

(5) Type V (0.746–0.799) includes 9.5% of the evaluation units. Type V units are located at the edge of urban agglomeration, and have low land-use efficiency and a low level of economic development.

High land-use efficiency units formed a few large groups with Jinan-Zibo, Qingdao and Weihai as cores (Figure 2). Land-use efficiency in the peripheral zones shows a decreasing gradient, while areas of low land-use efficiency show a scattered point distribution. Regional spatial spillover and linkage effects are especially significant in the Jinan-Zibo locus. The advantages of the core cities of Jinan and Zibo, such as in the technology industry, affect and effectively spread to adjacent areas, resulting in 7 units in the region achieving optimal land utilization efficiency of 1.000, which accounts for 53.8% of the total land use efficiency. The spatial spillover effect of coastal node cities is relatively low, and the spatial scales of Qingdao and Weihai are relatively large, resulting in relatively low land-use efficiency. The units having low land-use efficiency are mostly located on the boundaries and outer edges of high land-use efficiency groups. The spillover effects are significantly weaker than they could be and combinations of investment factors in these areas need to be optimized. Overall, land-use efficiency is high in Shandong Peninsula urban agglomeration. Type I and type II units accounted for 61.9% of the total area, whereas type IV and type V units accounted for 23.8% of the total area. The lowest land-use efficiency is 0.764.

The land-use efficiency of coastal areas (0.936) > that of inland areas (0.925) > that of northern areas (0.902) > that of southern areas (0.893). Land-use efficiency in coastal areas is high, but low in central inland areas. However, inland areas have land-use efficiency that is high in the core and low in the surrounding areas. The input factors in the coastal area of Jiaodong are more balanced than in inland units. The central belt of the Jiaodong coastal area and the marginal zones of inland units need to be optimized by adjusting input proportions. However, there is little incentive to optimize the inputs in Dongying due to abundant land resources and low population pressure. The spatial spillover effect of high land-use efficiency units is weak due to the relatively closed geographical boundaries. As a result, the land-use efficiency of the northern units is low, and only the urban areas reach type II. In contrast, the land-use efficiency of southern areas is low due to the low level of economic activity, unbalanced inputs and closed geographical boundaries.

There are 24 units (57%) that are increasing in income, mostly in the inland areas (13), followed by the coastal zones (7). Factor inputs are insufficient to match outputs. There are 13 units (31%) in which there is no change, 6 in each of the inland and coastal areas, and the input factors achieve maximum output. There are 5 units (11.9%) that are decreasing in income with redundant input factors (Table 2). In general, it is necessary to increase the inputs of factors in inland and coastal areas, and reduce the inputs of redundant factors in decreasing areas, to move land-use efficiency towards the optimum.

4.3 Spatial relationship between high-speed transportation superiority degree and land-use efficiency

We used a scatter diagram (Figure 3) to study the spatial relationship of high-speed transportation superiority to land-use efficiency. We combined land-use efficiency types with

Table 2 Land scale income in Shandong Peninsula urban agglomeration in 2014

Scale income	Areas
Increasing	Zhangqiu, Pingyin, Jiyang, Shanghe, Pingdu, Laixi, Gaoqing, Yiyuan, Kenli, Lijin, Laizhou, Penglai, Zhaoyuan, Qixia, Haiyang, Weifang, Qingzhou, Zhucheng, Anqiu, Gaomi, Linqu, Changle, Wulian, Juxian
Balanced	Jinan, Qingdao, Zibo, Huantai, Guangrao, Longkou, Laiyang, Shouguang, Changyi, Weihai, Rongcheng, Rushan, Zouping
Decreasing	Jiaozhou, Jimo, Dongying, Yantai, Rizhao

high-speed transportation types and classified the type combinations as follows: H-H (high land-use efficiency and high high-speed transportation superiority) includes types I-I, I-II, II-I and II-II; H-L (high land-use efficiency and low high-speed transportation superiority) includes types I-IV, II-IV and II-V; L-H (low land-use efficiency-high high-speed transportation superiority) includes types IV-I, IV-II and V-II; and L-L (low land-use efficiency and low high-speed transportation superiority) includes types IV-IV, IV-V and V-IV. All other type combinations are classified as M-M (medium land-use efficiency and medium high-speed transportation superiority). We refer to these five classes as land-use-transportation coordination categories.

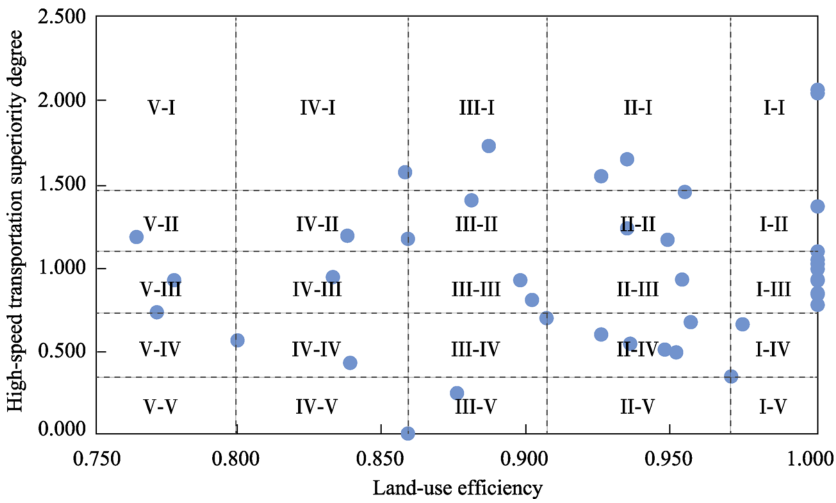

Figure 3 Combinations of types of land-use efficiency and high-speed transportation superiority degree in Shandong Peninsula urban agglomeration

We analysed land use-transportation coordination. Figure 4 shows that:

(1) 8 areas are H-H, 19% of the total. Most of them are regional centers and transportation hub cities (such as Jinan, Qingdao and Weihai) or regions peripheral to an important hub along a transportation link (such as Qingzhou, Jimo and Jiaozhou) which generally show a hub-spoke distribution along the Jiao-Ji and Qing-Yan-Wei-Rong rail lines.

(2) 7 areas are H-L, 16.7% of the total. Most of them are in the outer perimeter of hub cities and deviate from the main transportation arteries, and are affected by spatial spillover effects from the central city.

(3) 4 areas are L-H, 9.5% of the total. They are located mainly in the interstitial zones between the hub cities. Although they are along the main transportation links, they are weakly developed economically, and any spillover effects from the central city are weaker

than for surrounding areas.

(4) 4 areas are L-L, 9.5% of the total. They are far away from the hub cities and the main transportation links, and land-use efficiency and high-speed transportation construction lag behind all other areas.

(5) 19 areas are M-M, 45.2% of the total. They are the largest and the widest range of types. In these areas, land-use efficiency of areas adjacent to hub cities is often high because of the construction of high-speed transportation infrastructure, but it is low for areas far away from the hub cities.

There are spatial differences between areas of equivalent land use-transportation coordination. If we take the two hub cities of Jinan and Qingdao as the core, land use-transportation coordination is correspondingly high in Jinan, Qingdao, Weihai and Qingzhou, which are located in the hub-hub network and are in the area containing the main transportation link. As the distance from the hub city increases, the degree of spatial coordination declines. Land-use efficiency in these units often lags behind the high-speed transportation superiority degree, as can be seen in Weifang and Haiyang, which are far away from both the core hub cities. Land use-transportation coordination is L-L in Lijin, Kenli, and Wulian, which are widely dispersed and underdeveloped regions far away from hub cities and transportation links.

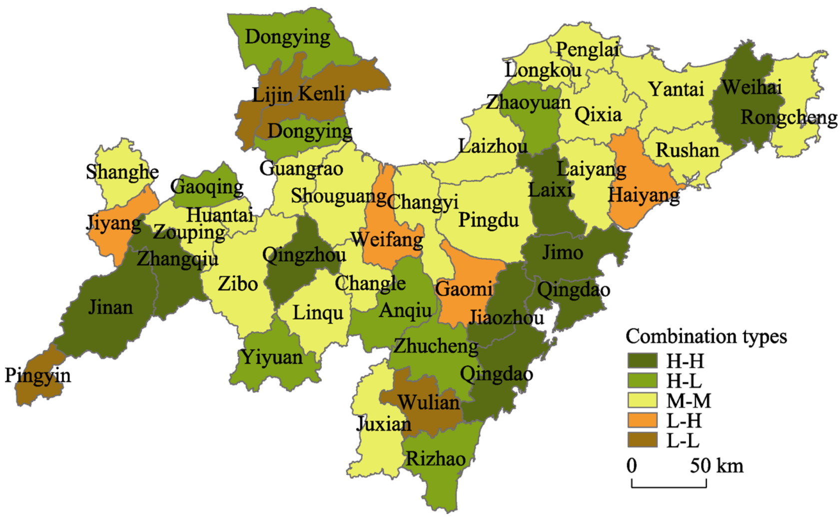

Figure 4 Spatial pattern of combined types of land-use efficiency and high-speed transportation superiority degree in Shandong Peninsula urban agglomeration

The preceding analysis shows there is a significant positive correlation between high-speed transportation modes and superiority index. Further analysis of the relationship between high-speed transportation modes and land-use efficiency showed that they closely related. We created different combinations of different modes of high-speed transportation and found that there is a positive relationship between land-use efficiency and the number of high-speed transportation modes (Table 3). This is because the key factor affecting land-use efficiency is the allocation of resources. In the dynamic process we have described, high-speed transportation can positively promote resource exchange through factor agglomeration and endogenous growth mechanisms. High-speed transportation can significantly increase regional advantages, and promote aggregation at points along high-speed transportation routes or trunks to form regional growth poles. The formation of these polar cores optimizes the development of land resources. The increase in modes of high-speed transportation diversifies the allocations, so land-use efficiency becomes more optimal. Land-use efficiency of the highway + high-speed rail + air transport combination is the highest, and 60% of the sample areas have the optimal value (1.000).

Table 3 Average land-use efficiency in areas with different combinations of high-speed transportation modes in Shandong Peninsula urban agglomeration

High speed transportation combination types	Species	Number of sample areas	Average land-use efficiency
Highway + High Speed Rail + Air Transportation	3	5	0.949
Highway + High Speed Rail	2	10	0.929
Highway + Air Transportation	2	1	0.799
Highway	1	23	0.921
High Speed Rail	1	1	1.000
None	0	2	0.907

High-speed transportation can also promote the exchange of resources between core cities and general cities through the hub effect. Core cities release excess resources to neighboring cities via high-speed transportation, and acquire their required resources through polarization effects. Non-core cities exchange resources with neighboring cities via high-speed transportation to mutual advantage. Goods and technological advantages are a form of spatial spillover from high-speed transportation, and spatial spillover will alter the spatial pattern of regional land-use efficiency (Figure 5). Land-use efficiency in transportation and economically less developed regions around Qingdao is relatively high, because of the concentration of resources due to the hub effect, which explains the H-L areas clustered on the periphery of the hub cities. Although Weifang and Yantai are types of highway + high-speed rail + air transportation, they have inadequate or redundant inputs. They are also distant from key cities such as Jinan and Qingdao. The corridor effect of the hub cities on these two cities has been weakened, resulting in lower land-use efficiency in these two areas than in the outlying areas of Jinan and Qingdao.

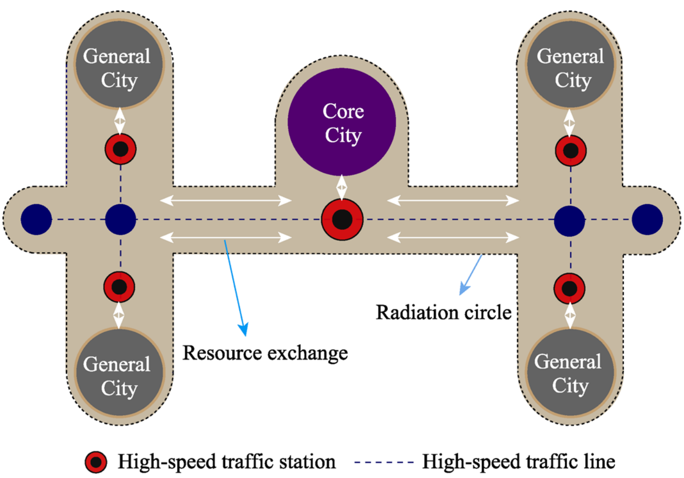

Figure 5 The influence of high-speed transportation on resource allocation

Shandong Peninsula urban agglomeration is mainly free from the constraints of the short-board effect caused by shortage of high-speed transportation facilities because the shortage is balanced by highway construction. This balance is seen at a macro level by high land-use efficiency. At the time of writing, the high-speed transportation network of the Shandong Peninsula has taken its initial shape, and it serves 95.2% of the region. The air transportation coverage rate was 14.3%, the high-speed rail coverage rate was 38.1%, and the highway coverage rate was 92.9%. These values show that the construction of highways is decisive in a high coverage rate for high-speed transportation networks. When we examine current land-use patterns in the Shandong Peninsula urban agglomeration, we see from the relative values that there are regional differences in land-use efficiency. The absolute values show that overall land-use efficiency is high level as the average value reaches 0.925. The difference between the maximum (1.000) and minimum (0.764) values is only 0.236, and 90.5% of the land-use efficiency is ⩾0.800. In comparison with the relative spatial variability of high-speed transportation superiority degree and land-use efficiency, the absolute spatial difference between the two is not significant, and it shows there is coordination between the two at the macro level.

In summary, by balancing reduced high-speed transportation construction with increased highway construction, the Shandong Peninsula urban agglomeration can avoid the short-board effect. Proper node layouts of high-speed rail stations and airports, will ensure that land-use efficiency is spatially well-balanced.

5 Conclusions and recommendations

With the aid of GIS, we created an evaluative high-speed transportation superiority degree system, and used the DEA model to examine the influence of high-speed transportation on land-use efficiency from different perspectives, taking the 42 counties of the Shandong Peninsula urban agglomeration as an example. The main conclusions are:

(1) There is significant spatial variation in the relationship between high-speed transportation superiority degree and land-use efficiency. Taking the two major hub cities of Jinan and Qingdao as the core, the surrounding counties (including the Qingzhou and Weihai sub-hubs) show significant high land use-transportation coordination which decreases as the distance from the hub cities increases. Land-use efficiency usually lags behind high-speed transportation superiority degree in areas along the transportation trunk routes, which are also distant from the hub cities. Land use-transportation coordination is low in areas that are distant from hub cities and transportation trunk routes.

(2) The number of high-speed transportation modes is positively related to land-use efficiency due to input and output consolidation and endogenous growth.

(3) High-speed transportation facilitates flows of goods, services and technologies between core cities and peripheral cities as space spillover (the hub effect). This alters the spatial pattern of regional land-use efficiency.

(4) The Shandong Peninsula urban agglomeration can eliminate the short-board effect caused by reducing high-speed transportation construction by balancing it with expressway (highway) construction. A proper node layout for high-speed rail stations and airports will increase land-use efficiency and provide a well-balanced spatial pattern.

There are significant inconsistencies between high-speed transportation construction and land-use efficiency in some areas. We make four recommendations to reduce them and thus improve coordination between high-speed transportation and land-use efficiency:

(1) We must improve the coverage of high-speed transportation, achieve full county-level coverage of highways, and complete prefecture-level coverage of high-speed rail stations and airports. We must also speed up the construction of the high-speed rail links in the Bohai Rim (Shandong section) and the Jinan-Qingdao section, and strive for the early completion of major airports such as Zibo and Rizhao (which have been opened by the end of 2015). If these are done then we will achieve a better balance of high-speed transportation in the Shandong Peninsula and efficient land use.

(2) We must accelerate the construction of high-speed transportation in underserved areas, such as Dongying and Rizhao, to achieve transport integration with hub cities and other important trunk routes and to increase the advantageous spillover of outside resources.

(3) We must optimize the high-speed transportation network along the coast of Jiaodong to increase accessibility to external transportation modes, to facilitate the movement of goods and services, and to create more convenient and smoother communication with the hinterland.

(4) Most importantly, we should recognize the importance of the positive effects of high-speed transportation construction. By coordinating land-use efficiency and high-speed transportation, we will simultaneously expand both to provide the greatest benefits.

References

Akkemik K A, 2005. Labor productivity and inter-sectoral reallocation of labor in Singapore (1965–2002). *Ge Growth Math Methods*, 30: 1–22.

Banker R D, Charnes A, Cooper W W *et al*., 1989. Constrained game formulations and interpretations for data envelopment analysis. *European Journal of Operational Research*, 40: 299–308.

Cervero R, Kang C D, 2011. Bus rapid transit impacts on land uses and land values in Seoul, Korea. *Transport Policy*, 18(1): 102–116.

Chapin F S, Kaiser E J, 1967. Urban Land Use Planning. 3rd ed. Illinois: University of Illinois Press.

Charnes A, Cooper W W, Rhodes E, 1978. Measuring the efficiency of decision making units. *European Journal of Operational Research*, 2(6): 429–444.

Debrezion G, Pels E, Rietveld P, 2011. The impact of rail transport on real estate prices: An empirical analysis of the Dutch Housing Market. *Urban Studies*, 48(5): 997–1015.

Defries R S, Foley J A, Asner G P, 2004. Land-use choices: Balancing human needs and ecosystem function. *Frontiers in Ecology & the Environment*, 2(5): 249–257.

Du D, 2016. The causal relationship between land urbanization quality and economic growth: Evidence from capital cities in China. *Quality & Quantity*, 51: 2707-2723.

Fang C L, Guan X L, 2011. Comprehensive measurement and spatial distinction of input-output efficiency of urban agglomerations in China. *Acta Geographica Sinica*, 66(8): 1011–1022. (in Chinese)

Gu Y Z, Zheng S Q, 2010. The impacts of rail transit on property values and land development intensity: The case of No.13 Line in Beijing. *Acta Geographica Sinica*, 65(2): 213–223. (in Chinese)

Guan Y J, Chen X J, 2013. A study on urban land use efficiency in Weinan City. *Urban Problems*, (10): 72–77. (in Chinese)

Guo Y Y, Li L, Li G C *et al*., 2015. Overview of interaction between urban land use and transportation. *Urban Planning International*, 30(3): 29–36. (in Chinese)

Jia Z H, Hao J M, 2011. Evaluation of urban land intensive utilization based on fuzzy comprehensive assessment method: A case study of Changzhi City. *China Population, Resources and Environment*, 21(12): 129–134. (in Chinese)

Jin F J, Wang C J, Li X W, 2008. Discrimination method and its application analysis of regional transport superiority. *Acta Geographica Sinica*, 63(8): 787–798. (in Chinese)

Johnson H M, 1960. Sociology: A Systematic Introduction. Paris: Allied Publishers.

Lambin E F, Geist H J, 2003. Regional differences in tropical deforestation. *Environment*, 45(6): 22–36.

Li M J, Chen G H, 2003. A review on the research and application of DEA. *Engineering Sciences*, 5(6): 88–94. (in Chinese)

Li X, Xu X X, Chen H H, 2005. Temporal and spatial changes of urban efficiency in the 1990s. *Acta Geographica Sinica*, 60(4): 615–625. (in Chinese)

Liu C G, Gao G P, Zhuang J, 2005. An empirical analysis of urban economic development and land use efficiency in Shandong Province. *China Economist*, (8): 257–259. (in Chinese)

Liu S H, Wu C J, Chen T, 2001. A critical review on the progress of urban land use theories in the West. *Geographical Research*, 20(1): 111–119. (in Chinese)

Liu X W, Zhang D X, Chen B M, 2008. Characteristics of China's town-level land use in rapid urbanization stage. *Acta Geographica Sinica*, 63(3): 301–310. (in Chinese)

Ma X, Chen X, Li X *et al*., 2018. Sustainable station-level planning: An integrated transport and land use design model for transit-oriented development. *Journal of Cleaner Production*, 170(1): 1052-1063.

Meng D Y, Shen J H, Lu Y Q, 2014. Evolvement of spatial pattern of county level transportation superiority in Henan, China. *Scientia Geographica Sinica*, 34(3): 280–287. (in Chinese)

Ou X, Feng C C, Shen Q Y, 2007. Application of synergisticity model in urban land-use potential appraisal. *Geography and Geo-Information Science*, 23(1): 42–45. (in Chinese)

Peneder M, 2003. Industrial structure and aggregate growth. *Structural Change & Economic Dynamics*, 14(4): 427–448.

Shen T, 2013. A review on land use at home and abroad. *Contemporary Economics*, (24): 156–157. (in Chinese)

Wang C X, Cui X G, Wang X Q, 2014. Analysis of Chinese "Urban Agglomerations Disease" phenomenon under new urbanization background. *Urban Development Studies*, 21(10): 12–17. (in Chinese)

Wang C X, Wang G F, Liu R C *et al*., 2010. Empirical research on evaluation model of transport superiority degree: A case study of Shandong Province. *Human Geography*, 25(1): 73–76. (in Chinese)

Wang X W, Wang S J, Song Y *et al*., 2015. Changchun land use spatio-temporal variation under the transportation elements' driving. *Economic Geography*, 35(4): 155–161. (in Chinese)

Wang Y P, Chen K M, Ma C Q, 2008. Quantitative analysis of coordination between rail transit network configuration and urban form. *Journal of Railway Engineering Society*, (11): 11–15. (in Chinese)

Wu D W, Mao H Y, Zhang X L *et al*., 2011. Assessment of urban land use efficiency in China. *Acta Geographica Sinica*, 66(8): 1111–1121. (in Chinese)

Wu Y, Hui E, Zhao P *et al*., 2018. Land use policy for urbanization in China. *Habitat International*, 77: 40-42.

Xu X, Peng H, Xu Q *et al*., 2009. Land changes and conflicts coordination in coastal urbanization: A case study of the Shandong Peninsula in China. *Coastal Management*, 37(1): 54-69.

Yang H Q, Hu Y, Wang Q X, 2015. Evaluation of land use efficiency in three major urban agglomerations of China in 2001–2012. *Scientia Geographica Sinica*, 35(9): 1095–1100. (in Chinese)

Yang Q K, Duan X J, Ye L *et al*., 2014. Efficiency evaluation of city land utilization in the Yangtze River Delta using a SBM-Undesirable model. *Resources Science*, 36(4): 712–721. (in Chinese)

Yu M, 2002. Data, Models and Decision. Beijing: China Machine Press, 196–198. (in Chinese)