ISSN: 2029-4913 / eISSN: 2029-4921

TECHNOLOGICAL and ECONOMIC DEVELOPMENT of ECONOMY

2025
Volume 31
Issue 1
Pages 184–210
https://doi.org/10.3846/tede.2024.21997

INFLUENCE FROM HIGHWAYS ON REGIONAL ECONOMIC GROWTH – BASED ON THE TRADE POTENTIAL IN CHINA

Xiaoli HU, Shanlang LIN, Ruofei LIN✉

International College of Football, Tongji University, Shanghai, China

Article History:
- received 20 August 2023
- accepted 12 May 2024
- first published online 17 September 2024

Abstract. The question of whether the construction of the highway network is economical and can produce positive economic benefits has been a hot topic of discussion in recent years. Previous scholars have explored the impact from multiple perspectives. Our paper draws the "trade potential" model proposed by Armstrong, based on the universal gravity model and the principle of space interaction, which is different from the traffic accessibility, market potential, and market access used in most of the literature. We argue that it is more appropriate to consider both the size impact and the time distance or trade cost impact of the two cities. The paper constructs a conceptual framework and theoretical model for the impact of highways on regional economic growth, measures the "minimum transit time" of highways between prefecture-level cities in China, and calculates the trade potential of prefecture-level cities. Through corresponding empirical model testing, we have obtained some meaningful conclusions.

Keywords: highway, trade potential, minimum transit time, spatial interaction, regional economic growth.

JEL Classification: O10, R18, R41.

✉Corresponding author. E-mail: ***1610007@tongji.edu.cn***

1. Introduction

The construction of China's highways started late, but it has developed rapidly. The opening of the Hujia Highway in 1988 and the Shenda Highway in 1990 was the prelude to the development of China's highways. By 2020, the total highway mileage nationwide had reached 161,000 kilometers, covering most prefecture-level cities (prefectures, states, and leagues) (National Bureau of Statistics, n.d.). Until December 31, 2020, a total of 16 provinces (Hong Kong, Macau, and Taiwan are not included in the statistics) have achieved county-county highways in China, and the number has been more than half. The highway network extending in all directions is an important symbol of China's transportation modernization, and it is also an important core asset of the country and various places within it.

However, the question of whether the construction of the highway network is economical and can produce positive economic benefits has also been a hot topic of discussion in recent years (Fu, 2016; Shi, 2009). To clarify this question, two other questions must be answered. First, considering that, in contrast to highways in other countries, the majority of Chinese highways are toll roads with higher unit freight costs compared to standard public roads, the question arises: can highways still foster regional economic growth in China, and if so, what mechanisms facilitate this growth? Second, does this "hard truth" have applicable conditions? In other words, the construction of the highway network has improved inter-regional accessibility, and promoted the spatial flow of production factors. Which regions will get more growth opportunities, and which regions may be damaged?

Regarding the role of highways in regional economic growth, there are two completely different theoretical opinions in the existing literature (Jiwattanakulpaisarn et al., 2012; Baum-Snow et al., 2017). However, most studies explain the mechanism of highways affecting regional economies from the perspectives of transportation costs and derived traffic accessibility, market potential, and market access (Datta, 2012; Duranton & Turner, 2012). While, most of China's highways are charged, and the unit transportation cost is higher than that of ordinary roads. Ignoring the uniqueness of China's highways, it is difficult to explain the relationship between highways and regional economic growth from the perspectives of transportation costs, traffic accessibility, market potential, and market access.

The concept of market potential and market access are derived from the market area theory of Reilly's retail store layout (Reilly, 1929); that is, the market area depends on the size of the target city and the distance to the target city. This was later developed by Harris (1954) and then expanded by Krugman (1991). The market area theory can more appropriately explain the market hinterland or market area of producers or retailers from a micro perspective, but it cannot easily explain the role of highways in regional economy growth from a macro perspective as it ignores the impact of the city of departure/origin. The calculated transportation costs, traffic accessibility, market potential, and market access, are also almost the same, because these indicators do not consider the impact of the city's own scale of departure/origin. It is difficult to explain the difference of the impact of highways on the economic growth of the two cities. How to more accurately understand the impact mechanism of highways on regional economic growth, and scientifically evaluate the relationship between highways and regional economic growth? That is still a problem needs to be explored and verified.

The main contributions of this paper are as follows: First, based on the universal gravity model and the principle of space interaction, the concept of "trade potential" of Armstrong (2007) is introduced, indicating that the growth potential of highway construction for the regional economy, different from most of the literature, uses concepts such as "traffic accessibility", "market potential", and "market access"[1]. Second, we have manually collected relevant data on the opening time of all highways at the prefecture-level city level, the time distance of highways (the time taken in highway travel) between cities, the entrance and exit settings, mileage, per capita mileage, density, and other related data, and, according to the theory of "space-time compression" of Janelle (1968), we use the OD-MATRIX cost matrix model to calculate the "minimum transit time" of highways between prefecture-level cities in China[2]. Third, based on the data analysis of China's highways, the general form of spatial interaction model is used to calculate the trade potential of cities at various levels, and the impact of highways on regional economic growth is empirically studied. Some studies have

[1] The concepts of "traffic accessibility", "market potential", and "market access" have similarities in specific applications. See the analysis below for details.

[2] The sample of this article includes all prefecture-level administrative regions and municipalities in China, namely municipalities, prefecture-level cities, autonomous prefectures, and league cities.

explored the changes in regional trade potential caused by highways, but researchers have rarely directly estimated the impact of trade potential on regional economic growth, this paper is a useful supplement to the existing research. Fourth, we used indicators such as network centrality, city size, and industrial structure, to conduct sub-sample regression based on regional economic heterogeneity, and yield meaningful conclusions.

The rest of the paper is arranged as follows: The Section 2 is a literature review and comment. The Section 3 analyzes the theoretical framework of the impact of highways on regional economic growth. The Section 4 is methods and data. The Section 5 is econometric regression and corresponding result analysis. The Section 6 is conclusions.

2. Related literature

Transport infrastructure is often considered an important determinant of economic growth in developing countries, improving poor transportation infrastructure networks is known as one of the policy tools that can promote growth in developing and middle-income countries (Ferrari et al., 2019; Nenavath, 2023). In fact, regardless of income level, transportation infrastructure is a key element of economic development (Irshad et al., 2023; Magazzino & Maltese, 2021). Due to the agglomeration effect, transportation infrastructure makes production factors more convenient for developed economies. However, the diffusion effect allows transportation infrastructure to promote the production technology level of neighboring regions as well (Li et al., 2020). As early as the 1940s, many development economists put forward many insightful ideas on the relationship between transport infrastructure and economic growth and regarded them as "socially advanced capital" (Rosenstein-Rodan, 1943). Transport infrastructure is seen as an important prerequisite for "economic take-off" (Rostow, 1960). Banister and Thurstain-Goodwin (2011) pointed out that transport infrastructure affects the regional economy at three different levels: output and productivity effects at the macro level, agglomeration economies and labor market effects at the meso level, and land and real estate market effects at the micro level. We are mainly concerned with the research literature at the macro level.

At the level of empirical research, attention to the relationship between highways and regional economic growth has its origin in the discussion of the US "productivity crisis" that began in the early 1970s. According to research, the average annual productivity growth rate in the US from 1948 to 1969 was 2.5%, and the average annual growth rate from 1969 to 1987 was 1.1% (Munnel, 1990). Some scholars refer to the low productivity growth rate during this period as a "productivity crisis" (Boarnet, 1998). Scholars such as Baily et al. (1985), Denison (1985), and Griliches (1988) tried to explain the root of the "productivity crisis", but these explanations are not generally regarded as convincing. Aschauer (1989) published a groundbreaking paper, calculating that the elasticity of output of infrastructure such as transportation was 0.39 and contending that the decline in US public capital (or infrastructure) investment was the root cause of the decline in productivity growth. If the public infrastructure stock increased by 10%, the productivity of private sector capital would increase from 3% to 5.6%. As highways account for 32% of all public capital (Gramlich, 1994), their impact on economic growth is obvious.

Since Aschauer's (1989) paper, many studies have measured the contribution of highway investment to economic growth, and they have reached two diametrically opposite conclusions. Most studies have concluded that highway construction promotes economic growth. Moreno and López-Bazo (2007) and Jiwattanakulpaisarn et al. (2011) measured the elasticity of highway output as being between +0.029 and +0.054. Pereira and Andraz (2004), Berechman et al. (2006), and Ozbay et al. (2007) found that highways have a positive impact on regional output. Holl (2016) and Chakrabarti (2018) conducted research on the highways in Spain and India, respectively, and found that they have a promoting effect on manufacturing productivity. Gao et al. (2015) contended that highways have increased the productivity of China's service industry, and Bu et al. (2019) contended that highways have corrected distortions and increased productivity. Mao et al. (2022) analyzed the impact of rapid transit development on urban economic growth in China, and found that the improvement of travel convenience brought about by the development of highways has significantly promoted urban economic growth.

Other studies have reached the opposite conclusion, arguing that highway construction has no significant impact on economic growth and can even have a negative impact. For example, Eisner (1991), Evans and Karras (1994), and Garcia-Milà et al. (1996) found that the impact was not significant according to US state highway research. Jiwattanakulpaisarn et al. (2012) studied the US interstate highways, non-state major roads, and local roads, and concluded that the long-term impact on output was small. Faber (2014) and Baum-Snow et al. (2020) considered that the output level of some regions (central cities or connected counties) was increased, whereas the output level of other regions was reduced. That was only redistribution of output. Why do different studies reach diametrically opposite conclusions? Some scholars have criticized the early research methods for reasons such as the existence of a causal relationship between the highway and the output, the omission of important variables (Gramlich, 1994), and the failure to consider the time lag of the highway (Jiwattanakulpaisarn et al., 2011), etc., which make the research conclusions biased.

At the macro level, regarding the mechanism of highway investment's influence on economic growth, the mainstream thinking is to inherit the viewpoints of classical location theory and Krugman's new economic geography and analyze the impact of highways on regional economic growth from the perspectives of transportation costs, traffic accessibility, market potential, and market access. Shirley and Winston (2004), Datta (2012) believed that highways reduce companies' inventory and logistics' costs. Faber (2014), Ghani et al. (2016), and Holl (2016) believed that highways reduce travel costs, time spent, and transportation costs. Holl (2004) and Rothenberg (2011) calculated accessibility according to Harris's (1954) formula, and Song et al. (2012) used time distance to calculate accessibility. They believed that the construction of highways increased regional accessibility and increased the attractiveness of business entry. It is worth noting that Baum-Snow et al. (2020), measured the changes caused by China's highways in the market potential in various regions, based on the market potential theory of Harris (1954) and Krugman (1991). They believed that areas with high market potential have shifted production factors from neighboring areas to obtain more favorable economic growth, and the economic growth of neighboring areas is at a disadvantage.

Unlike foreign highways, the vast majority of Chinese highways are toll roads with high tolls. Therefore, explaining the economic growth effect of highways from the perspective of transportation costs clearly has significant limitations. Accessibility is an important indicator for evaluating transportation infrastructure projects in transportation economics. However, this indicator only considers the distance or travel time between two places, as well as the attractiveness of the destination, ignoring the spatial interaction between the departure and destination. Moreover, it fails to reflect the core-periphery relationship of new economic geography. Therefore, the improvement of destination accessibility does not necessarily lead to economic growth. Because of this, many empirical literature has proven that improving accessibility does not necessarily lead to economic growth. Similar to accessibility, the indicator of "market access" only considers the cost of trade between the two places and the attractiveness of the destination, ignoring the spatial interaction between the departure and destination.

3. Theoretical framework

3.1. Interpretative framework from transportation costs to trade potential

The question of explaining the influence of highways on regional economic growth is related to the evaluation of the value of highway investments, which is a concern for domestic and foreign economists. The existing research mainly includes the following ideas:

3.1.1. Transportation costs

The first idea is to explain this influence from the perspective of transportation costs, which is a common method from Classical Location Theory to modern New Economic Geography Theory. However, compared with most foreign highways, China's highways are unique. Approximately 95% of China's highways implement the mechanism of "loaning roads and paying for loans". Most of them enact toll charges, and they have the characteristics of fast traffic speed, shortened travel time, and high transportation cost. Based on calculation of fuel consumption, tire wear, and maintenance costs of freight cars, the unit cost of China's highways is 252.74 yuan per kiloton-kilometer, which is 7.95% lower than the unit cost of ordinary roads and includes 1.30% lower fuel cost, 4.47% higher tire cost, and 43.02% lower overhaul cost (Liang, 2001). However, if the toll is added, the unit cost of a highway in China is 327.74 yuan per kiloton-kilometer, which is 20.12% higher than the unit cost of an ordinary road. As the transportation cost of China's highways is higher than is that of ordinary roads, it is difficult to explain the impact of highways on regional economic growth from the perspective of transportation costs.

3.1.2. Traffic accessibility

The second idea is to explain the influence from the perspective of traffic accessibility, which is a common method in management for transportation and economic geography. The measurement of traffic accessibility includes physical accessibility and space-time accessibility. Bhat et al. (2000) summarized and compared five methods commonly used in the research literature, among which the change of transit time is one of the most commonly used.[3] According to the study by Lin et al. (2018), the shortening of travel time brought about by highways in China has promoted economic growth as a whole, and there are large differences between regions.

However, as pointed out by Vickerman (1974), explaining regional economic growth in this way has significant limitations and may even lead to misleading conclusions. The first limitation lies in ignoring the traffic demand. Building a highway between two sparsely populated areas may not bring economic growth. Secondly, due to the different land development values in different regions, any time savings will have different values, and the accessibility calculated by the transit time ignores this feature. Again, it ignores the problem that changes in relative accessibility may shift existing traffic from one destination to another, possibly resulting in some regional factor inflow at the expense of a regional element outflow.

3.1.3. Market potential and market access

The third way of thinking about the influence of highways on regional economic growth is to explain it from the perspective of market potential[4] and market access. The concept of "market potential" can be traced back to the theory of the Market Areas between two cities proposed by Reilly (1929). Riley's law refers to the amount of trade that two cities attract from an intermediate town in the neighborhood, roughly proportional to the population of the city, and inversely proportional to the distance to the middle town. The general expression is:

$$\frac{B_i}{B_j} = \left(\frac{P_i}{P_j}\right)^N \left(\frac{D_j}{D_i}\right)^n, \tag{1}$$

where B_i is the trade volume that city i attracts from the middle town T in the neighboring area. B_j is the trade volume that city j attracts from the middle town T in the neighboring area. P_i is population of city i, P_j is population of city j. D_i is the distance from city i to the middle town T of the neighboring area. D_j is the distance from city j to the middle town T of the neighboring area. N and n are two constants.

Harris (1954) used the concept of "Market Potential" proposed by Colin Clark to analyze whether the location choices of US producers are close to the urban market. Market potential is calculated based on the target market size and Euclidean distance. It is used to measure the potential market size and quantity that a production enterprise can obtain. The formula is equivalent to the concept of physics "field". The general expression is:

$$MP_i = \sum_{j=1}^{R} M_j / d_{ij}, \tag{2}$$

where MP_i is the market potential of the production area i, M_j is the size of the target market city j, and d_{ij} is the Euclidean distance between the city i and the city j. Market potential measures the possible spatial distance between producer choice and urban market, similar to Riley's market area.

[3] Another common method is the gravity model, which is the same as the market potential measurement method of economics.

[4] In some literature, "Economic Potential" is also used instead of "Market Potential".

Krugman (1991) derived market potential from the wage equation, with the expression:

$$MP_i = \sum_{j=1}^{R} \tau_{ij}^{1-\sigma} \times E_j / G_j^{1-\sigma}, \tag{3}$$

where, MP_i is the market potential of the production city i, $\tau_{ij}^{1-\sigma}$ is the transaction cost between city i and city j, σ is the product substitution elasticity, E_j is the consumption expenditure of city j, and G_j is the price index of city j. Compared with Harris's (1954) market potential, the replacement of Euclidean distance is the transaction cost between the two places, which depends not only on the geographical distance but also on the degree of openness, trade barriers, and other factors; replacing the size of the target market city is the target market demand, depending on the market demand capacity, and the number and the price of competitive manufacturers. In fact, the market potential of Harris (1954) can be seen as a special case of Krugman's (1991) market potential.

Donaldson et al. (2016) replaced "market potential" with "market access". Market access depends, on the one hand, on the economic aggregate of the target market j, and, on the other hand, on the transportation costs between city i and city j with parameter assumptions, namely:

$$MA_i = \sum_{j=1}^{R} \tau_{ij}^{-\theta} GDP_j. \tag{4}$$

where τ_{ij} represents the transportation cost between city i and city j, including the transportation time and cost, and the degree of influence on the local market is $-\theta$. It can be seen that Donaldson's market access is a concept that lies between the market potential of Harris (1954) and Krugman (1991).

Both the market potential of Harris (1954) and Krugman (1991) and the market access of Donaldson et al. (2016) are essentially the same as Reilly's (1929) "market zone" concept, and they are all gravity models under the attractive constraints of the target market (Fotheringham & O'Kelly, 1989). Market potential and market access are suitable for the location selection of producers and retailers in micro-analysis, but they are not suitable for the macro analysis of the relationship between regions. As market potential and market access both consider only one city, that is, the size and quantity of the target market, the influence of the other city is ignored.

3.1.4. Trade potential

We argue that the analysis of the impact of highways on regional economic growth is more appropriate with the Spatial Interaction Model, considering both the size impact and the time distance or trade cost impact of the two cities. In fact, the spatial interaction model can be regarded as a two-dimensional constrained gravity model combining the gravity model of output constraint and the gravity model of attractive constraint, Vickerman (1974) called it the combined attraction accessibility index. He compared the accessibility and market potential commonly used in the literature and concluded that the combined attraction accessibility index associated with the spatial interaction model is the most satisfactory. To distinguish it from the concepts of market potential and market access commonly used in the literature, we draw the Trade Potential in Armstrong (2007) to represent the combined attraction accessibility index associated with the spatial interaction model. The difference between trade potential and market potential (market access) can be represented by Figure 1.

Similar to Newton's universal gravity model, the general expression of trade potential[5] is:

$$TP_{ij} = KO_i D_j f\left(C_{ij}\right). \tag{5}$$

where TP_{ij} is the trade potential between city i and city j, K is constant, O_i is the size of the starting city i, D_j is the size of the ending city j, and $f(C_{ij})$ is the trade cost between city i and city j.

The total city's trade potential denotes sum of trade potentials between city i and all other cities, which is expressed as:

$$TTP_i = \sum_{j=1}^{R} TP_{ij}. \tag{6}$$

The trade potential of a city i and any other city (TP_{ij}) accounts for the proportion of the total city's trade potential, which is called the trade potential membership degree (TTP_i). The expression is:

$$PTP_{ij} = \frac{TP_{ij}}{TTP_i}. \tag{7}$$

In the analysis of regional economic relations, trade potential is a good analytical tool. The highway's opening alters a region's trade potential, essentially reflecting its change in market scope and size obtained by either cost-effective or rapid access. And it indicates the strength and direction of mutual influence between the areas.

(1) Total city's trade potential (TTP) and its implications

TTP can reflect the network centrality of a city in the regional economy. Regional trade potential depends not only on the distance between cities but also on the size and quality of each. The sum of a city's trade potential can reflect its network centrality in the regional economy. For example, in the 13 cities of the Beijing–Tianjin–Hebei urban agglomeration, the total trade potential calculated based on the gross domestic product (GDP) of each city and the shortest transit time of the highway in 2018 of Beijing and Tianjin are 18453.5 and 16380.4, respectively, which is much higher than Langfang's 10608.8 (see Appendix, Table A1). This indicates the central position of Beijing and Tianjin in the Beijing–Tianjin–Hebei urban ag-

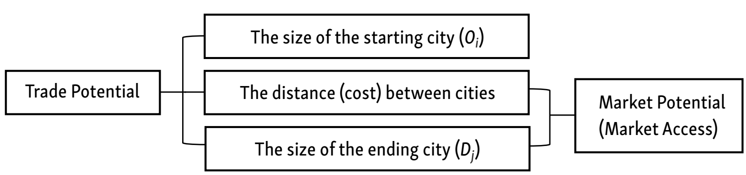

Figure 1. Difference between trade potential and market potential (market access)

[5] The concept of "Trade Potential", commonly used in Baldwin (1994), Nilsson (2000) and Egger (2002), refers to the expected trade volume between countries. Armstrong (2007) redefines the potential of trade to represent the maximum possible transaction volume that can be achieved between two regions, rather than the average trade value in the previous analysis of the gravity model.

glomeration and also illustrates the dual-core structure of the agglomeration. The cities with the least centrality are Zhangjiakou and Chengde. The total trade potential of each of these is 1863.1 and 2132.8, respectively, which is 10.0% and 11.6% of that of Beijing, respectively.

(2) Trade potential membership degree (PTP) and its implications

PTP can reflect the spatial connection direction of a city. For example, Beijing–Langfang and Beijing–Tianjin trade potential account for 26.1% and 26.0% of the total of Beijing's trade potential, respectively (see Appendix, Table A2). Beijing's main economic connection directions are Langfang and Tianjin. The proportion of the trade potential of Tianjin–Beijing, Tianjin–Tangshan, Tianjin–Langfang, and Tianjin–Cangzhou to the total of Tianjin's trade potential is 29.3%, 18.4%, 16.7%, and 15.3%, respectively. Tianjin's main economic connection directions are Beijing, Tangshan, Langfang, and Cangzhou, in that order. The proportion of the trade potential of Qinhuangdao–Beijing, Qinhuangdao–Tangshan, and Qinhuangdao-Tianjin to the total trade potential of Qinhuangdao is 26.0%, 24.0%, and 18.8%, respectively. The main economic links of Qinhuangdao are Beijing, Tangshan, and Tianjin. It can be seen that the economic connection direction of the Beijing–Tianjin–Hebei urban agglomeration has urban network centrality and proximity; that is, the main direction of the economic connection direction is cities with large network centrality and neighboring cities.

3.2. Mechanism of highway affecting regional economic growth

The shortened highway transit time has brought about changes in the trade potential of various cities in China. In the existing literature at home and abroad, neither the spatial interaction model nor trade potential have been linked to economic growth and productivity. The change in trade potential caused by highways means that both the number and the size of markets available to a city have changed. Greater trade potential not only increases economic opportunities, makes the industrial division of labor more specialized, and utilizes economies of scale to a greater extent but also can increase more differentiated goods and diversified choices, thereby increasing competition and promoting productivity and economic growth. Therefore, we propose the following hypothesis:

H2: *The development of highways can promote regional economic growth through the enhancement of trade potential.*

Specifically, the impact of trade potential based on highways on regional economic growth is reflected in the following aspects: First, the reduction of travel time caused by transportation investment or service improvement can increase the face-to-face contact between businesses and families. Second, companies and families make location choices based on the advantages of travel time, resulting in traffic space intensification near nodes. Third, improvements in highway investment or services may lead to higher-density employment groups and even larger, denser, and more diverse cities and increase productivity. In addition, the construction of highways can reduce transportation costs between regions, increase trade between regions, promote the circulation of goods between regions, and enhance regional economic vitality.

The trade potential essentially refers to the market scope and scale that a region can obtain at the lowest cost or fastest speed, reflecting the changes in regional market potential caused by the construction of highways, and the strength and direction of mutual influence between regions after the opening of highways. Thus, the market potential exhibits gradient distribution characteristics due to distance, and directional characteristics due to differences in the time distance of highways. This will inevitably have different impacts on heterogeneous regions. The differences in urban centrality, market scope, and market potential represented by trade potential may also lead to differences in regional economy, thereby having heterogeneous impacts on regional economic growth. Therefore, we propose hypothesis 2:

H3: *The trade potential based on highways will have heterogeneous impacts on regional economic growth.*

4. Methods and data

4.1. Estimation approach

This paper extends the model of Lin (2017), and builds a regression model of regional economic growth based on trade potential as an independent variable:

$$ln(GDP)_{ct} = \lambda_0 + \lambda_1 ln(ttp)_{ct} + \lambda_2 V_t + \Omega_c + \delta_t + u_{ct}; \tag{8}$$

$$ln(indvalue)_{ct} = \lambda_0 + \lambda_1 ln(ttp)_{ct} + \lambda_2 V_t + \Omega_c + \delta_t + u_{ct}, \tag{9}$$

where, $ln(GDP)_{ct}$ represents the logarithmic value of GDP of city c in t year, and $ln(indvalue)_{ct}$ is the logarithmic value of total industrial output value of city c in t year. The independent variable of this paper is trade potential $ln(ttp)_{ct}$. λ_1 is the estimated coefficient of the independent variable. If $\lambda_1 > 0$ and is significant, it means that the construction of the highway network will obviously promote regional economic growth; otherwise it will inhibit regional economic growth. V_t is the control variable at the regional level, including fixed asset investment, employment scale, total volume of trade, foreign direct investment, and freight volume by other transportation. Ω_c is the area fixed effect. δ_t is a time effect. u_{ct} is the error term.

4.2. Variables and measures

4.2.1. Independent variable

The independent variable, trade potential, is measured as follows:

(1) Trade potential calculation formula

Therefore, we use formula (5) as the basic model to measure the regional trade potential. We set K in the formula to be constant 1, and O_i and D_j are the resident populations of the two cities, respectively. $f(C_{ij})$ is the cost of trade, assuming that the unit price of the same mode is the same in various modes of transportation, so the difference in trade costs is reflected in the difference in travel time or distance, and the road resistance coefficient is taken as 2 (Reilly, 1929), $f\left(C_{ij}\right) = d_{ij}^{-2}$. Here, d_{ij} is the shortest transit time between O_i and D_j.

(2) Calculation of shortest transit time

To calculate the shortest transit time between two cities, we establish an electronic map of the highway network from 2000 to 2015. We use ArcGIS to obtain and draw the vector electronic map of the highway in the latest year. The Geographic Information System (GIS) layer is sourced from the 2018 Gaode map. The layer contains related information of all open highways, national roads, and railways until December 2015. The latest version of the map in the road network is used for calibration. We manually determine the opening time, starting point, and ending point of each highway, and finally generate a highway electronic map for each year from 2000 to 2015. As the highway network did not fully cover all prefecture-level cities in China between the sample years (2000 to 2015), to avoid having a large number of missing samples we merge the national road network of 2014 into the highway network electronic map, and use national roads where there are no open highways. We use the average highway 100 km/h and the national road 60 km/h for calculation.

We calculate the shortest transit time between the center of each prefecture-level city (that is, the seat of the city government), and use two layers of highways and national roads. The specific steps are as follows: find the shortest transit path between the two cities, and then calculate the shortest transit time between the two cities based on the shortest transit path, including the shortest transit time of the highway and the shortest time from the city center to the entrance of the highway. The calculation formula is:

$$d_{ij} = d_{ir_1} + d_{jr_2} + d_{r_1 r_2}, \tag{10}$$

where d_{ir_1} is the shortest transit time from the center of O_i to the nearest highway intersection r_1, d_{ir_2} is the shortest transit time from the center of D_j to the nearest highway intersection r_2, and $d_{r_1 r_2}$ is the shortest transit time between the highway intersection r_1 and r_2.

(3) Trade potential measurement

According to formula (5), we calculate the trade potential (TP_{ij}) of each city to all other cities in China from 2000 to 2015.

Then, we sum the trade potential of each city and all other cities according to formula (6). The total trade potential (TTP_i) of each prefecture-level city from 2000 to 2015 is obtained, as shown in Figure 2.

As shown in Figure 2, the pattern of trade potential shows a spatial imbalance, declining gradually from the central city to the surrounding areas and then the border areas. The trade potential of each city presents a "core–periphery" circle structure, that is, the "core" cities often have greater trade potential, whereas most of the edge nodes have smaller trade potential. The figure shows that the region with the greatest trade potential has always been around the Huang-Huai-Hai Plain and the middle and lower reaches of the Yangtze River and has declined gradually in the northwest, northeast, and southwest directions.

Highways have improved the trade potential of prefecture-level cities, but the changes have been uneven. The construction of the highway network has greatly improved the absolute trade potential of the marginal areas. From 2000 to 2015, the trade potential of Henan, Hubei, Anhui, Shandong, the middle and lower reaches of the Yellow River, and the middle reaches of the Yangtze River changed slightly, and the trade potential of thebottom cities located on the edge of the northeast, northwest, southwest, and southeast coastal areas changed the most. Cities with poor trade potential have improved; in particular, Tibet and western Sichuan and Qinghai are in the process of significant improvement. Eastern Inner Mongolia, Yunnan, Guizhou, and Hunan have also improved significantly. In general, highways have improved the conditions of locations in the west, border areas, and mountain areas, and the southeast coastal areas have also improved. It can be seen that the creation of highways has improved the border locations of the country, strengthened the trade potential of these remote areas, and produced a significant space–time contraction effect, thereby reducing the gap between the core and the border areas.

4.2.2. Dependent variables

The dependent variables, the regional GDP (*GDP*) and the gross industrial output value (*ind-value*) of each city are deflated by the GDP deflator and industrial output index, respectively, to obtain the real GDP and industrial output levels and eliminate the time trend.

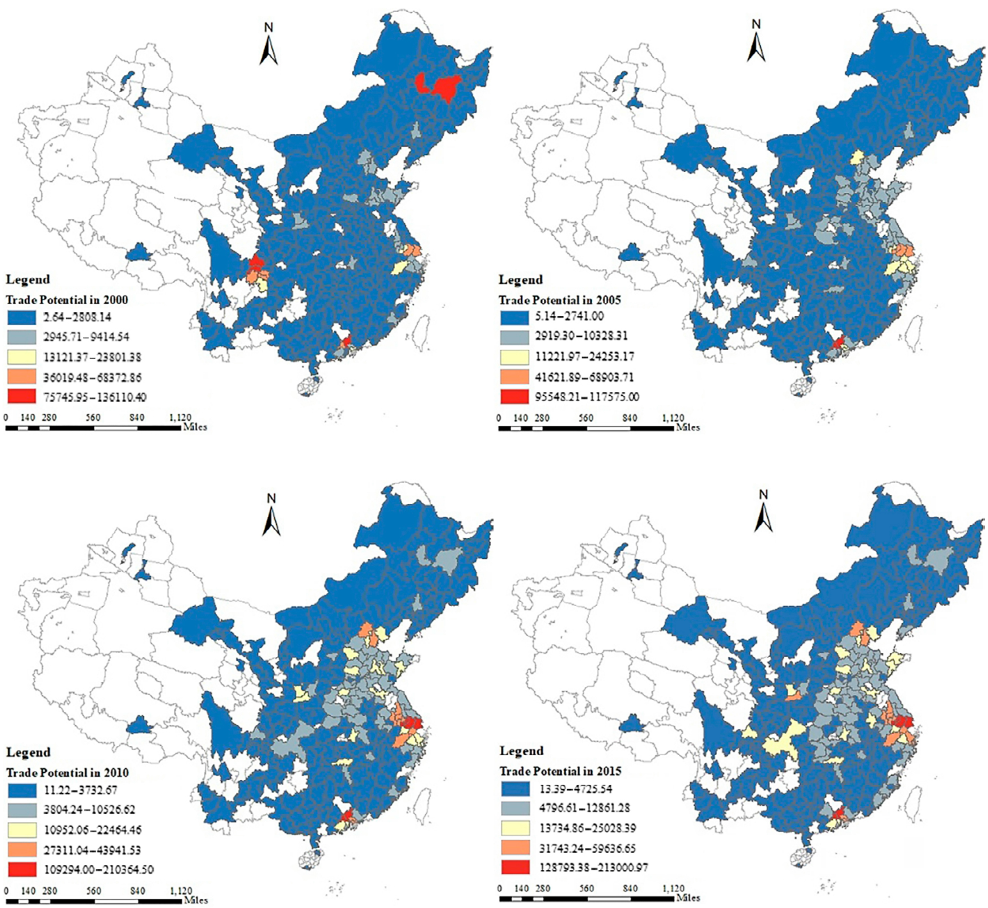

Figure 2. Trade potential of prefecture-level cities in 2000, 2005, 2010, and 2015

4.2.3. Control variables

We select six control variables in the model. These are: railway freight volume (*frail*), road freight volume (*froad*), fixed asset investment (*finvest*), employee employment (*employee*), total volume of trade (*trade*), foreign direct investment (*fdi*), patent grants (*patent*), and fiscal expenditure (*finance*) in each city. The specific variables are as follows:

The railway freight volume (*frail*) and the highway freight volume (*froad*) in each city represent the impact of railway and road transportation modes on economic growth.

The investment in fixed assets (*finvest*) is an important factor driving economic growth, which will not only directly affect the current economic growth but also promote subsequent production and services and further promote economic development.

The number of employed people (*employee*) in each region can reflect the level of purchasing power and consumption to a certain extent, which affects regional economic growth.

Total volume of trade (*trade*) reflects the total external trade of cities, which can promote regional economic development, promote regional industrial structure upgrade, ease regional employment pressure, and thus promote economic growth.

Foreign direct investment (*fdi*) cannot only make up for the shortage of funds in regional economic development but also may bring in the introduction of foreign technology, which may increase the economic activity of prefecture-level cities through either direct technology introduction or indirect stimulation of capital, thereby bringing regional economic growth.

The number of patent grants (*patent*) represents the state of regional innovation. Regional innovation has always been an important factor and a supporting condition to promoting economic development, and it has a positive impact on regional economic growth.

The financial expenditure (*finance*) of each city can stimulate domestic demand, thereby greatly promoting regional economic growth.

The definitions of the main variables are shown in Table 1.

Table 1. Definition of main variables

Variable type	Variable	Symbol	Meaning
Dependent variables	The regional gross domestic product (100 million yuan)	*GDP*	Regional overall economic development level
	The gross industrial output value (100 million yuan)	*indvalue*	Industrial development level
Independent variable	Trade Potential	*ttp*	Trade potential of cities based on the economic connection between highways
Control variables	Railway freight volume (10,000 tons)	*frail*	Total freight volume by rail
	Road freight volume (10,000 tons)	*froad*	Total freight volume by road
	Fixed assets investment (100 million yuan)	*finvest*	Total fixed assets minus increase in fixed assets
	Employment in the whole society (10,000 people)	*employee*	Total number of employed people in all levels of the city
	Total volume of trade (US$10,000)	*trade*	Import and export trade level
	Foreign direct investment (100 million yuan)	*fdi*	Direct capital investment and technical knowledge spillovers
	Number of patent licenses	*patent*	Technological development level
	Government fiscal expenditure	*finance*	Financial expenditure (100%)

4.3. Data description

The data of prefecture-level cities come mainly from the "China City Statistical Yearbook" (National Bureau of Statistics of China, n.d.-a), the "China Statistical Yearbook for Regional Economy" (National Bureau of Statistics of China, n.d.-b), the "China Transport Statistical Yearbook" (National Bureau of Statistics of China, n.d.-c) and statistical bulletins and the prefecture-level cities' transportation bureau website over the years 2000–2015.

We collect data for 274 prefecture-level cities from 2000 to 2015. As the magnitudes of different variables are quite different, their heteroscedasticity will have a certain effect on the results of empirical estimation. To weaken the impact, some variables are first taken into natural logarithms and then incorporated into the model. Stata14 (https://www.stata.com/stata14/) was used for data analysis, descriptive statistics of each regression variable after processing are shown in Table 2.

As shown in Figure 3, we give a scatter plot of the relationship between trade potential and GDP and industrial added value. It can be seen directly from Figure 3 that, after removing other factors, the trade potential change brought by highways has a significant positive correlation with GDP and industrial added value.

Table 2. Descriptive statistics of regression variables

Variable name	Observations	Maximum	Minimum	Average	Standard deviation
ln_GDP	4384	10.152	2.886	6.424	1.143
ln_ indvalue	4384	8.939	0.924	5.483	1.326
ln_ ttp	4384	12.271	0.972	7.026	1.779
ln_ froad	4384	11.462	2.996	8.393	0.976
ln_ frail	4384	10.398	0.000	5.630	2.240
ln_ finvest	4384	12.806	1.606	5.733	1.384
ln_ employee	4384	7.490	0.000	5.232	0.754
ln_ trade	4384	18.005	0.000	10.991	2.355
ln_ fdi	4384	14.564	0.000	9.046	2.146
ln_ patent	4384	11.680	0.000	5.597	2.119
ln_ finance	4384	8.731	0.495	4.369	1.196

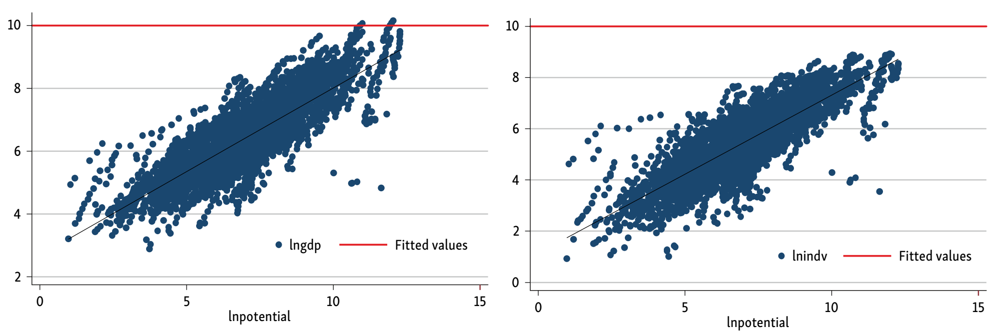

Figure 3. (Left) trade potential and GDP, (Right) trade potential and industrial added value

5. Results and analysis

5.1. Benchmark regression

The independent variable is set as the city's trade potential, and the dependent variables are total GDP and industrial output value, a Hausman-test is performed based on the regression equations (9) and (10). The result denotes that the P value is 0.0000, the Fixed effect model is appropriate.

The results of the Fixed effect regression model are shown in columns (1) and (2) of Table 3. There is a significant positive correlation between the trade potential brought by highways and the logarithm of GDP and the logarithm of industrial output value. The elasticity of the independent variable *ln_ ttp* to the GDP logarithm is 0.080 and significant at the level of 1%. That is, if the regional trade potential brought by highways changes by 1%, this will boost the regional GDP growth by 0.080%. The independent variable *ln_ ttp* has an elasticity of 0.109 for the industrial output value logarithm and is significant at the level of 1%. That is, if the regional trade potential brought by highways changes by 1%, this will boost the regional industrial output value by 0.109%.

Table 3. Regression of the impact of trade potential on regional economic growth

	(1)	(2)
Variable	*ln_GDP*	*ln_ indvalue*
ln_ ttp	0.080*** (16.50)	0.109*** (13.85)
ln_ froad	0.008 (1.43)	0.014 (1.57)
ln_ frail	0.002 (0.94)	0.012*** (2.92)
ln_ finvest	0.124*** (17.98)	0.197*** (17.74)
ln_ employee	0.132*** (10.89)	0.008 (0.39)
ln_ trade	0.026*** (6.98)	0.050*** (8.25)
ln_ fdi	–0.001 (–0.30)	0.013*** (3.26)
ln_ patent	0.014*** (4.16)	0.001 (0.27)
ln_ finance	0.469*** (48.64)	0.452*** (29.05)
_cons	1.971*** (25.65)	0.722*** (5.83)
R^2	0.966	0.933
Observations	4384	4384

Notes: ***, ** and * indicate significance at the levels of 1%, 5%, and 10%, respectively.

The data in "()" in the table is the t-statistic of the heteroscedasticity. The following tables is the same.

It can be seen that regional trade potential changes based on the opening of highways are of great significance to regional economic growth, which verifies the hypothesis 1. According to the strength of trade potential, regions with greater network centrality are more conducive to regional economic growth; conversely, regions with smaller network centrality are more unfavorable to regional economic growth. This conclusion is significantly different from the conclusion of Faber (2014). Faber (2014) contended that the highway network reduces the economic growth gap between central and peripheral cities. Our conclusions are logically similar to those of Lu et al. (2018) in respect of railways. Lu et al. (2018) held that shorter railway transportation times are more conducive to economic growth, and the larger the city size, the greater the economic growth effect. However, our conclusions differ from those of Lu et al. (2018) in two points:

First, two cities that both have strong network centrality and shorter transportation time and distance brought by highways are conducive to economic growth. The regional trade potential depends not only on the time distance between regions but also on the size of the economy between regions. In other words, two cities with large economic scale, large network centrality, and shorter transportation time and distance brought by highways have greater trade potential, which is more conducive to economic growth.

Secondly, cities with shorter transportation time and distance due to highways and more market scope can benefit economic growth. In addition to the reduction of transportation time and distance brought by highways, the improved inter-city accessibility is more conducive to economic growth.

5.2. Robustness checks

First, we replace the explanatory variable with highway mileage density. The highway mileage density refers to the highway construction mileage divided by the land area. As some highways in the prefecture-level cities have been built more lately, the highway mileages have more zero values. To avoid a large number of missing samples caused by the zero-value logarithm, we sum all the highway mileages to one and then take the logarithm. The number density is also processed accordingly.

The regression results are shown in Table 4. Columns (1) and (2) use the logarithm of GDP as the independent variable, and the logarithm of highway mileage density as the indepen-

Table 4. Robustness check: the impact of highway mileage density on economic growth

Variable	(1)	(2)
	ln_GDP	*ln_ indvalue*
ln_ ttp	0.001^{***} (1.63)	0.008^{***} (2.87)
Control Variables	YES	YES
_cons	2.276^{***} (28.85)	1.195^{***} (9.50)
R^2	0.964	0.931
Observations	4384	4384

dent variable, then we derive the results of fixed effect. When the logarithm of GDP is used as the dependent variable, the coefficient of *ln_ ttp* is significantly positive at the confidence level of 1%; that is, there is a significant positive correlation between the mileage density of highways and the total amount of GDP, indicating that the greater the mileage of highway network construction, the better the regional economic growth. As the logarithm of industrial output value is taken as the dependent variable, the empirical results are still significant.

Second, the independent variables are replaced by market potential based on highways. Combined with the previous literature and the research content of this article, the calculation formula of market potential is as follows:

$$MA_i = \sum_j \tau_{ij}^{-\theta} G_j, \tag{11}$$

where MA_i represents the market potential of city i, τ_{ij} represents the transportation cost between cities, which is calculated by the shortest transit time of the highway between two cities; G_j is used to represent the market size of city j, that is indicated by the city's permanent population.

Donaldson (2018) used India's interregional trade data and estimated the value of θ to be about 3.6. Tombe and Zhu (2019) set the value of θ as 4 based on the literature review. Xu (2017) based on Simonovska and Waugh (2014) estimated the value of θ as 4, and Lin (2017) set the value of θ as 3.6. We set the values of θ as 3.6 and 4, respectively, the empirical results are shown in Table 5.

The regression coefficients are still significantly positive, indicating that the increase in market potential based on highways has a significant role in promoting regional economic growth. The model is robust.

In short, the robustness checks of the two methods show that the conclusions are robust and that the construction of the highway network has a significant role in promoting regional economic growth.

5.3. Endogeneity discussion

Considering that there is a two-way relationship of influence between the independent variables and the dependent variable, there may be endogenous problems. The estimated coefficients obtained only by OLS regression methods with fixed effect models may be biased.

Table 5. Robustness check: the impact of highway market potential on economic growth

Variable	θ = 3.6		θ = 4	
	ln_GDP	*ln_ indvalue*	*ln_GDP*	*ln_ indvalue*
ln_MA	0.006*** (3.62)	0.001*** (1.09)	0.001*** (1.38)	0.002*** (2.41)
Control Variables	YES	YES	YES	YES
_cons	2.250*** (28.94)	1.119*** (9.01)	2.263*** (29.23)	1.124*** (9.10)
R^2	0.964	0.930	0.964	0.930
Observations	4384	4384	4384	4384

To effectively overcome the problems caused by the above conditions to the equation estimation, we use two methods to test for endogeneity.

The first approach is to use the first-order lagged trade potential as a proxy variable and use the system generalized method of moments (SYS-GMM) to estimate. The results are shown in Table 6, columns (1) and (2). The coefficient symbols and significance of the variables are basically consistent with the aforementioned empirical result.

The second is to use highway mileage density in 1962 as an instrumental variable for highways. The instrumental variable must satisfy two conditions at the same time, that is, it is relevant to highways and exogenous to economic growth. This paper refers to the method of Baum-Snow et al. (2017) and takes 1962 highway mileage density as the instrumental variable. In terms of relevance, the roads in the 1950s and 1960s adopt the polity of "rely on the local, rely on the masses, the popularity as the main purpose", of which most are simple roads and cart road constructed relying on "voluntary work by farmers, building by civilian and support by the government, and work-for-the-dole". In 1962, highways were basically classified as off-grade highways. The mileage without road surface accounted for 43.2%, and the mileage open to traffic in rain and sunshine accounted for only 48.9%. The construction of off-grade highways is greatly affected by topography, and modern highway construction is also affected by it. Baum-Snow et al. (2017) also found that areas with more highways in 1962 had more highways in 2010. Therefore, the highway mileage density in 1962 meets the requirements of relevance to highways. As far as exogeneity is concerned, the highways built in the 1950s and 1960s were not only simple in technology and low-level, but also the main role of them was to transport agricultural products, while the transportation of raw materials and industrial products between big cities and provincial capitals was undertaken by railways. Coupled with the strict control of population movements, even a large number of urban populations have migrated to rural areas, and the urbanization rate is very low, with only 17.33% in 1962. Therefore, it is difficult for the highway in 1962 to play a role in modern economic growth led by industrialization and urbanized 50 years later, which basically meets the exogenous requirements of modern economic growth[6].

As the historical data of 1962 do not change with time, we multiplied the highway mileage density in 1962 by the year (*ln_ road_density***year*). We use this density as a proxy variable for trade potential. The results are shown in Table 6, columns (3) and (4). The sign of the regression results is consistent with the foregoing.

5.4. Heterogeneous analysis

On the basis of the above regression, to further judge the impact of highways on different types and different sizes of areas, this paper divides the cities into three categories: urban population size, urban network centrality, and proportion of tertiary industry. Sub-sample regressions are performed to further analyze the heterogeneous regions.

5.4.1. Sub-sample regression by city size

According to the size of their permanent population, cities are divided into three groups: City

[6] For the demonstration and test of the validity of this instrumental variable, see Baum-Snow et al. (2017), which will not be repeated here.

I, City II, and City III. City I refers to cities with a population of more than 5 million, City II refers to cities with a population of 2–5 million, and City III refers to cities with a population of less than 2 million. Using trade potential as an independent variable, the regression results are shown in Table 7. The independent variable coefficients are all positive, that is, the trade potential change brought by the highway has a clear positive correlation with the total GDP, which has a significant effect on promoting regional economic growth. In comparison, the impact of trade potential on the GDP and industrial output value of City II is greater than is the impact on both City I and City III.

5.4.2. Sub-sample regression by city network centrality

Based on Taylor and Derudder's (2015) global urban interlocking network mode (Interlocking Network Mode), we draw on the core (city) calculation method of Hennemann and Derudder (2014) and build the urban network centrality evaluation model on the basis of Chinese producer service enterprises. Then, we organize the top 100 largest domestic management advisory corporations, accounting firms, law firms, advertising, banking, securities, insurance, and other industries (excluding companies with fewer than two subsidiaries), and the datasets of foreign multinational companies that have branches in these industries in China. The data come from the "Qixinbao" website (https://www.qixin.com/). The data of this website are updated synchronously with the website of the State Administration for Industry and Commerce.

Table 6. Endogenous test: First-order lagged trade potential and highway mileage density in 1962

Variable	(1)	(2)	(3)	(4)
	ln_GDP	*ln_ indvalue*	*ln_GDP*	*ln_ indvalue*
Lln_ ttp	0.092*** (16.57)	0.189*** (19.81)		
*ln_ road_density*year*			0.010*** (19.94)	0.007*** (7.80)
Control Variables	YES	YES	YES	YES
_cons	0.777*** (16.23)	–0.595*** (–7.02)	–80.056*** (–19.39)	–51.534*** (–7.64)
R^2	0.959	0.905	0.967	0.934
Observations	4110	4110	4352	4352

Table 7. Sub-sample regression results by city size

	ln_GDP			*ln_ indvalue*		
	City I	City II	City III	City I	City II	City III
ln_ ttp	0.064*** (7.51)	0.110*** (9.94)	0.069*** (10.42)	0.082*** (6.47)	0.146*** (8.22)	0.094*** (8.35)
Control Variables	YES	YES	YES	YES	YES	YES
_cons	1.136*** (7.24)	2.205*** (20.51)	1.669*** (10.98)	–0.492** (–2.10)	0.914*** (4.97)	0.251 (1.02)
R^2	0.975	0.968	0.958	0.955	0.933	0.919
Observations	1363	2221	800	1363	2221	800

The Qixinbao website can query the genealogy of related companies, obtain the registered addresses and industry fields of enterprises and their investment holding companies, obtain corporate space organization level data, and assign 0–5 to the headquarters, first-level, second-level, and third-level subsidiaries.

The inter-city connectivity of enterprise j between cities a and b is:

$$r_{abj} = v_{aj} \times v_{bj}, \tag{12}$$

where v_{aj} and v_{bj} are the service value of enterprise j in cities a and b;

The inter-city connectivity of all companies between cities a and b is:

$$r_{ab} = \sum_{j=1}^{m} r_{abj}. \tag{13}$$

Thus, the service value matrix V of m enterprises in n cities is constructed. Based on this, referring to the calculation method of the core (city) district of Hennemann and Derudder (2014), the urban network centrality is calculated. The total network connectivity of city a is:

$$TNC_a = \sum_{i=1}^{n} r_{ai} \left(a \neq i \right). \tag{14}$$

According to the above methods, the centrality of China's urban networks is evaluated.

According to their network centrality, cities are divided into three groups: high centrality, medium centrality, and low centrality. Using trade potential as an independent variable, the regression results are shown in Table 8. The independent variable coefficients are all positive; that is, the trade potential change brought by highways has a clear positive correlation with the total GDP, which has a significant effect on promoting regional economic growth. In comparison, the impact of trade potential on the GDP and industrial output value of cities with medium centrality is greater than is that on cities with either high centrality or low centrality. In other words, compared with cities with high network centrality and low network centrality, the economic development of cities with medium network centrality is more sensitive to trade potential.

Table 8. Sub-sample regression results by urban network centrality

	ln_GDP			*ln_ indvalue*		
	High centrality	Medium centrality	Low centrality	High centrality	Medium centrality	Low centrality
ln_ ttp	0.088*** (9.70)	0.181*** (13.96)	0.053*** (7.96)	0.106*** (6.02)	0.177*** (7.60)	0.081*** (7.40)
Control Variables	YES	YES	YES	YES	YES	YES
_cons	1.735*** (12.35)	2.261*** (23.63)	2.419*** (16.88)	0.764*** (3.03)	0.490*** (2.64)	0.805*** (3.39)
R^2	0.949	0.932	0.877	0.839	0.822	0.794
Observations	1461	1461	1462	1461	1461	1462

5.4.3. Sub-sample regression by industry structure

The sample is divided into three groups according to the proportion of the tertiary industry, and the impact of highway construction on regional economic growth is tested under the condition of the differential development of the tertiary industry. The regression results are shown in Table 9. According to Table 9, the role of highways in regional economic development has become increasingly significant, directly affecting regional industrial layout, optimization, and adjustment. The change in trade potential brought by the construction of highways has a promoting effect on regions with different proportions of tertiary industry, with an obvious promoting effect on regions with medium proportions of tertiary industry and a relatively minimal impact on regions with a low proportion of tertiary industry.

Table 9. Sub-sample regression results by the proportion of tertiary industry

	ln_GDP			*ln_ indvalue*		
	High proportion	Medium proportion	Low proportion	High proportion	Medium proportion	Low proportion
ln_ ttp	0.087^{***} (10.78)	0.094^{***} (8.53)	0.060^{***} (8.01)	0.098^{***} (8.28)	0.115^{***} (6.46)	0.077^{***} (6.80)
Control Variables	YES	YES	YES	YES	YES	YES
_cons	1.754^{***} (13.93)	2.614^{***} (17.59)	2.228^{***} (17.50)	0.419^{**} (2.26)	1.410^{***} (5.25)	1.134^{***} (5.94)
R^2	0.961	0.967	0.963	0.925	0.926	0.938
Observations	1459	1462	1463	1459	1462	1463

The above sub-sample regression conclusions according to city size, urban network centrality, and the proportion of tertiary industry are logically consistent. For medium-sized cities, medium network-centrality cities, and cities with a medium tertiary industry ratio, the impact of highways is higher than is that of the other two samples, which verifies the hypothesis 2. We believe that the root cause lies in the different sensitivity of different products and industries to tolled highways. The manufacturing proportion of medium-sized cities and medium network-centrality cities is relatively high, but most of them are dominated by deep processing and heavy chemical industries, which have high added value and are less sensitive to highway transportation costs, and the economic growth is relatively highly dependent on highway freight transportation.

6. Conclusions

Although China's toll collection on highways has increased unit transportation costs, the shortening of transit time has increased the regional trade potential, which has had a profound impact on the spatial pattern of China's regional economic growth. The conclusion of this article is mainly divided into two parts: in theory, according to the universal gravitation model and the principle of spatial interaction, the concept of "trade potential" is introduced, which not only considers the scale of the two cities, but also considers the time distance between the two cities or the impact of trade costs.

We construct a theoretical explanation framework and theoretical model for highway's influence on regional economic growth. Through empirical research, we draw the following conclusions: First, the construction of highways causes the trade potential of cities along the lines of the highways to show an upward trend and presents a "core-periphery" circle structure, decreasing from the center to the outer layer. Second, the trade potential based on highway construction plays a significant role in promoting regional economic growth. The greater the trade potential, the more beneficial it is to regional economic growth. After replacing the independent variable and the dependent variable, the regression results are robust. At the same time, the impact of the trade potential on regional economic growth is much larger than is the market potential of highways, indicating that using market potential as highway variables will underestimate the impact on economic growth. Third, based on data from branches of producer service companies, we evaluate the network centrality of each city and combine the indicators of city size and industrial structure to perform sub-sample regressions on regional economic heterogeneity, obtaining meaningful conclusions. The sample is divided into three groups – high, medium, and low – according to city size, network centrality, and the proportion of tertiary industry. Of the three samples, highways have the largest impact on medium-sized cities, with medium network centrality and medium tertiary industries. The root cause is the different sensitivity of different products and industries to tolled highways.

Although we have carried on the theoretical and empirical exploration in this article, there are still some limitations. On the one hand, in theoretical model construction, time cost is not reflected as a single variable in the model, but a concept combined with transportation cost, while the time distance and time cost are important categories to reflect the characteristics of highway accessibility. On the other hand, in the empirical study, the data of highway are measured by city mileage and opening time, but not by the number and scope of highway entrances and exits, which is generally considered as an important factor affecting regional economic growth. That may restrict the depth of the analysis in this paper.

In the future research, we will further introduce more independent variables according to the characteristics of highway accessibility, so that the spatial model can reflect the uniqueness of the highway. We will analyze the impact of highway on regional economic growth on a smaller spatial scale based on its entrance and exit, which can make the empirical conclusions more accurate.

Data availability

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

Funding

This research was funded by the National Social Science Foundation of China, grant number 23BJY039.

References

Armstrong, S. P. (2007). *Measuring trade and trade potential: A survey* (Crawford School Asia Pacific Economic Paper, No. 368). https://doi.org/10.2139/ssrn.1760426

Aschauer, D. A. (1989). Is public expenditure productive? *Journal of Monetary Economics*, *23*(2), 177–200. https://doi.org/10.1016/0304-3932(89)90047-0

Baily, M. N., Chakrabarti, A. K., & Levin, R. C. (1985). Innovation and productivity in U.S. industry. *Brookings Papers on Economic Activity*, (2), 609–639. https://doi.org/10.2307/2534447

Baldwin, R. E. (1994). *Towards an integrated Europe* (Vol. 25). Centre for Economic Policy Research.

Banister, D., & Thurstain-Goodwin, M. (2011). Quantification of the non-transport benefits resulting from rail investment. *Journal of Transport Geography*, *19*(2), 212–223. https://doi.org/10.1016/j.jtrangeo.2010.05.001

Baum-Snow, N., Brandt, L., Henderson, J. V., Turner, M. A., & Zhang, Q. (2017). Roads, railroads, and decentralization of Chinese cities. *Review of Economics and Statistics*, *99*(3), 435–448. https://doi.org/10.1162/REST_a_00660

Baum-Snow, N., Henderson, J. V., Turner, M. A., Zhang, Q., & Brandt, L. (2020). Does investment in national highways help or hurt hinterland city growth? *Journal of Urban Economics*, *115*, Article 103124. https://doi.org/10.1016/j.jue.2018.05.001

Berechman, J., Ozmen, D., & Ozbay, K. (2006). Empirical analysis of transportation investment and economic development at state, county and municipality levels. *Transportation*, *33*, 537–551. https://doi.org/10.1007/s11116-006-7472-6

Bhat, C., Handy, S., Kockelman, K., Mahmassani, H., Chen, Q., & Weston, L. (2000). *Development of an urban accessibility index: Literature review* (Report No. TX-01/77-4938-1). University of Texas at Austin. Center for Transportation Research.

Boarnet, M. G. (1998). Spillovers and the locational effects of public infrastructure. *Journal of Regional Science*, *38*(3), 381–400. https://doi.org/10.1111/0022-4146.00099

Bu, X., Zhang, T., & Zhang, S. (2019). The road to prosperity: A study on the efficiency of resource allocation in China's highway construction. *Management World*, *355*, 44–63.

Chakrabarti, S. (2018). Can highway development promote employment growth in India? *Transport Policy*, *69*, 1–9. https://doi.org/10.1016/j.tranpol.2018.05.009

Datta, S. (2012). The impact of improved highways on Indian firms. *Journal of Development Economics*, *99*(1), 46–57. https://doi.org/10.1016/j.jdeveco.2011.08.005

Denison, E. (1985). *Trends in American economic growth*. Brookings Institution Press.

Donaldson, D. (2018). Railroads of the Raj: Estimating the impact of transportation infrastructure. *American Economic Review*, *108*(4–5), 899–934. https://doi.org/10.1257/aer.20101199

Donaldson, D., & Hornbeck, R. (2016). Railroads and American economic growth: A "market access" approach. *The Quarterly Journal of Economics*, *131*(2), 799–858. https://doi.org/10.1093/qje/qjw002

Duranton, G., & Turner, M. A. (2012). Urban growth and transportation. *Review of Economic Studies*, *79*(4), 1407–1440. https://doi.org/10.1093/restud/rds010

Eisner, R. (1991). Infrastructure and regional economic performance: Comment. *New England Economic Review*, (9), 47–58.

Egger, P. (2002). An econometric view on the estimation of gravity models and the calculation of trade potentials. *World Economy*, *25*(2), 297–312. https://doi.org/10.1111/1467-9701.00432

Evans, P., & Karras, G. (1994). Are government activities productive? Evidence from a panel of US states. *The Review of Economics and Statistics*, 1–11. https://doi.org/10.2307/2109821

Faber, B. (2014). Trade integration, market size, and industrialization: Evidence from China's National trunk highway system. *Review of Economic Studies*, *81*(3), 1046–1070. https://doi.org/10.1093/restud/rdu010

Ferrari, C., Bottasso, A., Conti, M., & Tei, A. (2019). The economics of transport infrastructure. In *Economic role of transport infrastructure: Theory and models* (pp. 5–38). Elsevier. https://doi.org/10.1016/B978-0-12-813096-4.00002-0

Fotheringham, A. S., & O'Kelly, M. E. (1989). *Spatial interaction models: Formulations and applications* (Vol. 1, p. 989). Kluwer Academic Publishers.

Fu, W. (2016). Highway construction requires capacity reduction. *International Financial News*. http://finance.sina.com.cn/roll/2016-09-26/doc-ifxwevww1546661.shtml

Gao, X., Long, X., & Yang, G. (2015). Transportation infrastructure and service industry development: Evidence from county-level highways and enterprise data from the second economic census. *Management World*, (8), 81–96.

Garcia-Milà, T., McGuire, T. J., & Porter, R. H. (1996). The effect of public capital in state-level production functions reconsidered. *The Review of Economics and Statistics*, *78*(1), 177–180. https://doi.org/10.2307/2109857

Ghani, E., Goswami, A. G., & Kerr, W. R. (2016). Highway to success: The impact of the golden quadrilateral project for the location and performance of Indian manufacturing. *The Economic Journal*, *126*(591), 317–357. https://doi.org/10.1111/ecoj.12207

Gramlich, E. M. (1994). Infrastructure investment: A review essay. *Journal of Economic Literature*, *32*(3), 1176–1196.

Griliches, Z. (1988). Productivity puzzles and R&D: Another nonexplanation. *Journal of Economic Perspectives*, *2*(4), 9–21. https://doi.org/10.1257/jep.2.4.9

Harris, Z. S. (1954). Distributional structure. *Word*, *10*(2–3), 146–162. https://doi.org/10.1080/00437956.1954.11659520

Hennemann, S., & Derudder, B. (2014). An alternative approach to the calculation and analysis of connectivity in the world city network. *Environment and Planning B: Urban Analytics and City Science*, *41*(3), 392–412. https://doi.org/10.1068/b39108

Holl, A. (2004). Transport infrastructure, agglomeration economies, and firm birth: Empirical evidence from Portugal. *Journal of Regional Science*, *44*(4), 693–712. https://doi.org/10.1111/j.0022-4146.2004.00354.x

Holl, A. (2016). Highways and productivity in manufacturing firms. *Journal of Urban Economics*, *93*, 131–151. https://doi.org/10.1016/j.jue.2016.04.002

Irshad, R., Mehr-un-Nisa & Ghafoor, N. (2023). Infrastructure and economic growth: Evidence from lower middle-income countries. *Journal of the Knowledge Economy*, *14*(1), 161–179. https://doi.org/10.1007/s13132-021-00855-1

Janelle, D. G. (1968). Central place development in a time-space framework. *The Professional Geographer*, *20*(1), 5–10. https://doi.org/10.1111/j.0033-0124.1968.00005.x

Jiwattanakulpaisarn, P., Noland, R. B., & Graham, D. J. (2011). Highway infrastructure and private output: Evidence from static and dynamic production function models. *Transportmetrica*, *7*(5), 347–367. https://doi.org/10.1080/18128600903479638

Jiwattanakulpaisarn, P., Noland, R. B., & Graham, D. J. (2012). Marginal productivity of expanding highway capacity. *Journal of Transport Economics and Policy* (*JTEP*), *46*(3), 333–347.

Krugman, P. (1991). Increasing returns and economic geography. *Journal of Political Economy*, *99*(3), 483–499. https://doi.org/10.1086/261763

Li, B., Gao, S., Liang, Y., Kang, Y., Prestby, T., Gao, Y., & Xiao, R. (2020). Estimation of regional economic development indicator from transportation network analytics. *Scientific reports*, *10*(1), Article 2647. https://doi.org/10.1038/s41598-020-59505-2

Liang, W. (2001). Analysis on the factors of the increase and decline of transportation cost of highway and ordinary highway vehicles. *Hebei Qiye*, *10*, 28–29.

Lin, S., Ye, W., & Zhang, L. (2018). Impact of time effect to the location of manufacturing films – Analysis on the relationship between highway network and new manufacturing films. *China Industrial Economics*, *2*, 137–156.

Lin, Y. (2017). Travel costs and urban specialization patterns: Evidence from China's high speed railway system. *Journal of Urban Economics*, *98*, 98–123. https://doi.org/10.1016/j.jue.2016.11.002

Lu, j., Du, Q., & Sun, P. (2018). Time cost, city size and economic growth per capita: An empirical analysis based on railway time data. *Management World*, *34*, 74–85.

Magazzino, C., & Maltese, I. (2021). Transport infrastructures: Investments, evaluation and regional economic growth. *Research in Transportation Economics*, *88*, Article 101125. https://doi.org/10.1016/j.retrec.2021.101125

Mao, J., Tian, Q., & Lu, C. (2022). Impact of rapid transit development on urban economic growth: An empirical study of the urban agglomerations in China. *Frontiers in Earth Science*, *10*, Article 920796. https://doi.org/10.3389/feart.2022.920796

Moreno, R., & López-Bazo, E. (2007). Returns to local and transport infrastructure under regional spillovers. *International Regional Science Review*, *30*(1), 47–71. https://doi.org/10.1177/0160017606296728

Munnel, A. (1990). How does public infrastructure affect regional performance? An overview. *Proceedings of a Conference held at Harwich Port*, *Massachusetts*, *Federal Reserve Bank of Boston*, *MA*, 69–103.

National Bureau of Statistics. (n.d.) https://www.stats.gov.cn/sj/

National Bureau of Statistics of China. (n.d.-a). *China city statistical yearbook 1990–2023*. China Statistics Press. https://data.cnki.net/

National Bureau of Statistics of China. (n.d.-b). *China statistical yearbook for regional economy 2001–2014*. China Statistics Press. https://data.cnki.net/

National Bureau of Statistics of China. (n.d.-c). *China transport statistical yearbook 2010–2022*. China Statistics Press. https://data.cnki.net/

Nenavath, S. (2023). Does transportation infrastructure impact economic growth in India? *Journal of Facilities Management*, *21*(1), 1–15. https://doi.org/10.1108/JFM-03-2021-0032

Nilsson, L. (2000). Trade integration and the EU economic membership criteria. *European Journal of Political Economy*, *16*(4), 807–827. https://doi.org/10.1016/S0176-2680(99)00060-9

Ozbay, K., Ozmen-Ertekin, D., & Berechman, J. (2007). Contribution of transportation investments to county output. *Transport Policy*, *14*(4), 317–329. https://doi.org/10.1016/j.tranpol.2007.03.004

Pereira, A. M., & Andraz, J. M. (2004). Public highway spending and state spillovers in the USA. *Applied Economics Letters*, *11*(12), 785–788. https://doi.org/10.1080/1350485042000254593

Reilly, W. J. (1929). *Methods for the study of retail relationships* (University of Texas Bulletin No. 2944). Bureau of Business Research.

Rosenstein-Rodan, P. N. (1943). Problems of industrialisation of eastern and south-eastern Europe. *The Economic Journal*, *53*(210–211), 202–211. https://doi.org/10.2307/2226317

Rostow, W. W. (1960). *The stages of economic growth: A non-communist manifesto*. Cambridge University Press.

Rothenberg, A. D. (2011). *Transport infrastructure and firm location choice in equilibrium: Evidence from Indonesia's highways* (Job Market Paper). University of California, Berkeley. https://www.researchgate.net/publication/265888586_Transport_Infrastructure_and_Firm_Location_Choice_in_Equilibrium_Evidence_from_Indonesia%27s_Highways

Shi, B. (2009). Faced with doubt, what should the highway do. *New Views*, *New Doctrines*, *Academic Salon Collection 26: The Relationship between the National Highway Network and Economic and Social Development* (pp. 80–84).

Shirley, C., & Winston, C. (2004). Firm inventory behavior and the returns from highway infrastructure investments. *Journal of Urban Economics*, *55*(2), 398–415. https://doi.org/10.1016/j.jue.2003.11.001

Simonovska, I., & Waugh, M. E. (2014). The elasticity of trade: Estimates and evidence. *Journal of international Economics*, *92*(1), 34–50. https://doi.org/10.1016/j.jinteco.2013.10.001

Song, Y., Lee, K., Anderson, W. P., & Lakshmanan, T. R. (2012). Industrial agglomeration and transport accessibility in metropolitan Seoul. *Journal of Geographical Systems*, *14*, 299–318. https://doi.org/10.1007/s10109-011-0150-z

Taylor, P., & Derudder, B. (2015). *World city network: A global urban analysis* (2nd ed.). Routledge. https://doi.org/10.4324/9781315730950

Tombe, T., & Zhu, X. (2019). Trade, migration, and productivity: A quantitative analysis of China. *American Economic Review*, *109*(5), 1843–1872. https://doi.org/10.1257/aer.20150811

Vickerman, R. W. (1974). Accessibility, attraction, and potential: A review of some concepts and their use in determining mobility. *Environment and Planning A: Economy and Space*, *6*(6), 675–691. https://doi.org/10.1068/a060675

Xu, M. (2017). *Riding on the new silk road: Quantifying the welfare gains from high-speed railways* (Job Market Paper). University of California, Davis.

APPENDIX

Table A.1. TP_{ij} of 13 cities in Beijing–Tianjin–Wing based on highways in 2018

	Beijing	Tianjin	Shijiazhuang	Tangshan	Baoding	Langfang	Cangzhou	Hengshui	Xingtai	Handan	Zhangjiakou	Chengde	Qinhuangdao	sum
Beijing		4802.3	861.6	2067.9	1427.4	4814.4	1561.8	594.7	354.9	398.2	784.3	786.0	642.4	18453.5
Tianjin	4802.3		621.1	3007.9	1042.5	2741.6	2510.5	512.6	273.8	307.5	198.8	361.8	464.8	16380.4
Shijiazhuang	861.6	621.1		233.3	782.6	339.3	562.3	732.7	1091.9	1039.5	152.3	78.6	70.4	6495.2
Tangshan	2067.9	3007.9	233.3		303.8	732.2	484.7	159.0	100.0	116.7	135.1	415.3	591.3	7755.9
Baoding	1427.4	1042.5	782.6	303.8		574.0	694.2	473.3	270.9	286.8	129.2	88.8	81.4	6073.7
Langfang	4814.4	2741.6	339.3	732.2	574.0		639.0	232.0	128.8	144.0	134.6	128.9	168.4	10608.8
Cangzhou	1561.8	2510.5	562.3	484.7	694.2	639.0		558.7	207.6	230.7	88.9	92.2	116.3	7630.7
Hengshui	594.7	512.6	732.7	159.0	473.3	232.0	558.7		415.2	431.1	56.6	40.8	40.6	4206.8
Xingtai	354.9	273.8	1091.9	100.0	270.9	128.8	207.6	415.2		2472.4	52.6	32.4	34.0	5400.6
Handan	398.2	307.5	1039.5	116.7	286.8	144.0	230.7	431.1	2472.4		61.5	38.7	39.5	5527.1
Zhangjiakou	784.3	198.8	152.3	135.1	129.2	134.6	88.9	56.6	52.6	61.5		69.2	38.4	1863.1
Chengde	786.0	361.8	78.6	415.3	88.8	128.9	92.2	40.8	32.4	38.7	69.2		179.9	2132.8
Qinhuangdao	675.0	488.4	74.0	621.3	85.5	176.9	122.2	42.6	35.7	41.5	40.3	189.0		2592.3

Note: The data was calculated by the author based on indicator.

Table A.2. PTP_{ij} of 13 cities in Beijing–Tianjin–Wing based on highways in 2018 (%)

	Beijing	Tianjin	Shijiazhuang	Tangshan	Baoding	Langfang	Cangzhou	Hengshui	Xingtai	Handan	Zhangjiakou	Chengde	Qinhuangdao
Beijing		26.0	4.7	11.2	7.7	26.1	8.5	3.2	1.9	2.2	4.3	4.3	3.5
Tianjin	29.3		3.8	18.4	6.4	16.7	15.3	3.1	1.7	1.9	1.2	2.2	2.8
Shijiazhuang	13.3	9.6		3.6	12.0	5.2	8.7	11.3	16.8	16.0	2.3	1.2	1.1
Tangshan	26.7	38.8	3.0		3.9	9.4	6.2	2.1	1.3	1.5	1.7	5.4	7.6
Baoding	23.5	17.2	12.9	5.0		9.5	11.4	7.8	4.5	4.7	2.1	1.5	1.3
Langfang	45.4	25.8	3.2	6.9	5.4		6.0	2.2	1.2	1.4	1.3	1.2	1.6
Cangzhou	20.5	32.9	7.4	6.4	9.1	8.4		7.3	2.7	3.0	1.2	1.2	1.5
Hengshui	14.1	12.2	17.4	3.8	11.3	5.5	13.3		9.9	10.2	1.3	1.0	1.0
Xingtai	6.6	5.1	20.2	1.9	5.0	2.4	3.8	7.7		45.8	1.0	0.6	0.6
Handan	7.2	5.6	18.8	2.1	5.2	2.6	4.2	7.8	44.7		1.1	0.7	0.7
Zhangjiakou	42.1	10.7	8.2	7.2	6.9	7.2	4.8	3.0	2.8	3.3		3.7	2.1
Chengde	36.9	17.0	3.7	19.5	4.2	6.0	4.3	1.9	1.5	1.8	3.2		8.4
Qinhuangdao	26.0	18.8	2.9	24.0	3.3	6.8	4.7	1.6	1.4	1.6	1.6	7.3	

Note: The data was calculated by the author based on indicator.