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Original Research

Highways and Green Economic Growth in China's Yangtze River Economic Belt: Mediating Role of Green Technology Innovation

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Abstract

Highway construction reduces the production costs of enterprises, which is conducive to their increased investment in environmental management and the adoption of green production technologies, thereby promoting regional green economic growth. Traditional research mainly focuses on the pollution problem in the transportation infrastructure and transportation process, and it is difficult to explain the spatial spillover problem of the green economy brought by transportation. We measured the shortest passage time and market access of the Yangtze River Economic Belt highway from 2005 to 2019. Meanwhile, we measured the green total factor productivity based on the Malmquist-Luenberger index. The empirical results show that highway construction has a significant role in promoting green economic growth in the Yangtze River Economic Belt. However, there is obvious regional heterogeneity in the degree of effect. Market access has the largest effect in large cities, followed by medium cities, and has the smallest effect on small cities. This suggests that there is an environmental "bottoming-out effect" in highway-induced industrial transfer. Further, we find that green technology innovation is the mechanism by which highways affect green economic growth.

Keywords: highways, green economic growth, green technology innovation, the Yangtze river economic belt, market access

Introduction

Since the 20th century, global warming and other global environmental problems have occurred frequently. People realize that traditional economic growth has already cost mankind dearly, and it is urgent to seek theories and methods that can improve the ecological environment and ensure sustainable development. In the 2009 report titled "OECD and Green Growth", the OECD introduced the concept of "green economic growth" within the framework of sustainable development. The notion of "green economic growth" aims to foster economic advancement and progress while safeguarding the continued provision of resources

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and environmental services by natural assets, which are essential for our well-being. Presently, the concepts of the green economy and green growth have gained widespread adoption. Scholars both domestically and internationally have conducted extensive research on the trends and factors influencing green growth, leading to numerous valuable findings [1].

Since the implementation of economic reforms and opening up, China's rapid economic growth has been closely linked to the development of transportation infrastructure, particularly highways [2]. The establishment of an extensive highway network serves as a significant indicator of China's modernization in transportation. Although China embarked on highway construction relatively late, it progressed rapidly, with the inauguration of the first mainland Chinese highway named "Hujia Highway" in October 1988. As of 2020, the total length of highways reached 161,000 kilometers, with 64,000 kilometers situated within the Yangtze River Economic Belt, accounting for 39.6% of the overall mileage. Moreover, as efforts to advance the development of the Yangtze River Economic Belt persist, highway construction will continue to expand. The "14th Five-Year Plan" for the Comprehensive Transportation System of the Yangtze River Economic Belt, published by the National Development and Reform Commission, outlines further optimization of the highway transportation network. This includes the establishment of eastward, westward, southward, and in-land external corridors to enhance the network's capacity and accessibility to the public. Consequently, determining whether the construction of the highway network aligns with the green growth requirements of the Yangtze River Economic Belt becomes an immediate and practical question that necessitates prompt attention.

There exists a consensus among scholars regarding the economic growth effects of transportation infrastructure [3]. Researchers have examined its impact on market access, trade flows, productivity, knowledge spillovers and innovation, population mobility, and various other aspects [4-8]. However, it is important to note that while transportation infrastructure can facilitate economic growth, it does not necessarily promote green economic growth in the same manner. The transformation from economic growth to green economic growth requires the utilization of resources and energy in a more efficient manner. Simultaneously, it is evident that transportation infrastructure and the transportation industry itself contribute to ecological damage, increased energy consumption, and the heightened release of pollutants. Thus, the question arises: Does the development of transportation infrastructure support the promotion of green growth? Furthermore, what mechanisms influence its impact on green growth? There is a dearth of research on this topic both domestically and internationally, with the economics community, including environmental and transportation economics, largely remaining silent [9].

This paper introduces the concept of market access, which is measured based on the shortest travel time via highways. The concept aims to capture the changes induced by highways in regional factor flows, market scope, and market size. The study employed market access as an explanatory variable. The green total factor productivity, assessed using the Malmquist-Luenberger index of non-radial SBM directional distance, was used as a proxy variable for green economic growth. Additionally, the analysis incorporated other control variables and data to construct a panel dataset encompassing prefecture-level and above cities in the Yangtze River Economic Belt from 2005 to 2019. Through empirical testing, this research examined the impact of highway network development on green economic growth in the Yangtze River Economic Belt.

Compared with the existing literature, the marginal contributions of this paper are mainly the following: First, the research perspective is new. Traditional studies have mainly focused on pollution emissions from transportation infrastructure and transportation modes themselves. A small amount of literature deals with those brought about by transportation, and almost no literature directly studies the effects of the construction of highways on green economic growth. This paper builds a theoretical explanatory framework for the impact of highways on regional green economic growth, explaining how highways with higher transportation costs affect regional green economic growth issues. Second, the indicator measurement method is new. This paper improves and expands the measurement method for market access. For the first time, highway data are used to establish the two-by-two O-D matrix between cities in the Yangtze River Delta, which avoids the errors brought by the direct application of foreign parameters in the existing literature. Third, the theoretical mechanism is new. It is different from the previous classical location theory. Based on the C-P model of new economic geography and Porter's hypothesis, this paper introduces the market access caused by the opening of highways and its green technology innovation effect.

The following paragraphs are structured as follows: Section 2 provides a summary of the relevant literature review conducted previously. Section 3 describes the mechanism of highway construction's impact on green economic growth. Section 4 outlines the methodology and data utilized in this study, including the selection of appropriate measures and a description of the data employed. Section 5 discusses the empirical regression results. Section 6 further discusses the impact of highway construction-induced green technological innovation effects on green economic growth. Section 7 concludes the paper.

Literature Review

Green economic growth is an extension of the economic growth model, which advances economic progress through environmental protection and social sustainability [10]. Transportation plays an irreplaceable role in the pursuit of sustainable development. Existing literature on the influence of transportation infrastructure on green growth encompasses two main aspects: first, the emissions resulting from transportation facilities and tools themselves, and second, the spatial spillovers generated by transportation that foster green technological innovations.

Several studies discuss the environmental impacts of highways, focusing on both their construction cycle and operational emissions. In the operational phase, transportation infrastructure like highways contributes to activities classified as "carbon-intensive", such as private car usage [11]. Extensive research demonstrates that the transportation sector is a significant source of carbon emissions. According to the report by the World Bank, road transportation alone accounts for 72% of total carbon emissions in the transportation sector. In Asia, carbon emissions from the transportation sector continue to rise. Comparative studies examining the emission impacts of different modes of transportation reveal that traditional road transportation exhibits high pollution levels. Findings from related studies indicate that subways, railroads, and high-speed railways have positive effects on reducing environmental pollution, in contrast to road transportation [12-14].

Scholars have extensively examined the impact of infrastructure on air pollution. Considering that vehicle exhaust contributes to air pollutants, some argue that expanding road and highway networks leads to increased driving and more vehicles, resulting in higher levels of air pollutant emissions. Additionally, scholars suggest that the inadequate energy efficiency performance of the transportation infrastructure can result in excessive energy consumption. Moreover, empirical studies reveal significant variations in the level and direction of energy efficiency at different stages of transportation construction [15]. These investigations indicate that, over time, transportation infrastructure demonstrates improvements in energy efficiency.

However, other empirical studies have demonstrated that transportation infrastructure can facilitate knowledge spillovers and promote green innovation [9]. Road infrastructure, by reducing transportation costs for goods and travel and enhancing transport connectivity, not only enhances people's mobility but also facilitates the dissemination of technologies and knowledge, particularly those related to pollution reduction. Green innovation is a key driver of green economic growth [10]. Green innovation not only promotes affordable, environmentally friendly technologies, but also reduces the cost of environmental sustainability. Murad et al. used Danish data covering the period 1970-2002, to examine the association between technological innovation, environmental quality, and economic growth [16]. The results show that technological innovation is positively correlated with economic growth, and technological innovation tends to reduce carbon emissions. Du et al. collected data from 1996-2012 for 71 countries and examined the impact of technological innovation on CO_2 reduction [17]. The results show that technological innovation has a positive contribution to the reduction of CO_2 emissions.

Currently, there is limited literature on the impact of highways on green development. Existing literature primarily focuses on the environmental consequences of highway transportation itself, and there is a scarcity of research directly exploring the influence of highways on the spillover of green technologies and the green economy. Theoretical perspectives suggest that highway construction contributes to reducing motor vehicle emissions by enhancing vehicle mobility. Although highway construction projects alleviate congestion and reduce travel costs, particularly travel time, the additional capacity can also stimulate more traffic and travel demand, which can have adverse environmental effects. This phenomenon, known as the "induced demand effect" in transportation literature, has been investigated by He et al. in the context of China [18].

Theoretical Mechanisms

How do transportation facilities play a role in regional economic growth? Classical location theory, from Duenen's agricultural location theory to Liosh's market location theory, invariably explains the growth effects of transportation facilities through transportation costs. The new economic geography, while putting the issue of space and transportation costs back into the framework of mainstream economics for consideration. However, it still regards the reduction of transportation costs as the reason for the economic growth effect of transportation infrastructure. Unlike foreign highways, more than 90% of China's highways are toll roads with high transportation costs. If the time cost of highway transportation is not taken into account, the transportation cost of highways is not only higher than that of railroad transportation, but even higher than that of general highways. Transportation costs obviously do not explain the economic growth effect of highways well. This limitation also applies to the issue of regional green growth. Capasso et al. points out that the key and central issue of green economic growth is still economic growth [1]. The difference is that green growth is the more efficient and cleaner use of resources and the reduction of undesired outputs such as waste while maintaining economic growth.

Therefore, we introduce market access based on the shortest duration of the highway. Scholars generally agree that transportation infrastructure affects regional economic growth through the changes it brings in market access, trade flows and employment, and location selections of enterprises [4, 19, 20]. However, few scholars are concerned with the impact of transportation infrastructure on regional green economic growth through direct and indirect mechanisms [21]. This paper focuses more on the broader economic impacts. This paper argues that market access reflects changes in the scope of the market and the size of the market that a region can access at the lowest cost or the fastest speed through the highway. Thus, the opening of highways expands the market size of cities, shortens the time distance between cities, facilitates the mobility of labor and talent, and contributes to the spatial spillover effects of knowledge and technology, which, in turn, promotes green economic growth. In addition, the opening of highways promotes the integration of regional markets, thus creating an information transparency effect [22], strengthening environmental regulation, and promoting green economic growth.

Based on this, we propose Hypothesis 1.

Hypothesis 1: The opening of highways can promote regional green economic growth, but the extent of its role varies according to the heterogeneity of city size and city class.

According to the theory of ecological modernization, technology is an indispensable solution to address environmental degradation caused by rapid global economic growth [23]. However, technology may be a contributing factor to environmental degradation in some cases. Only those technologies that increase resource efficiency and promote cleaner production can help solve environmental problems. These technologies are referred to as green technologies. The development and application of green technologies manifest in green total factor productivity gains. A large number of scholars have proven the impact of green technology innovation on green economic growth [17, 24].

Scholars at home and abroad have actively researched the spatial spillover effects of transportation infrastructure. The source of the spatial spillover effect is usually divided into three aspects: sharing, matching, and learning effects. Among them, the learning effect refers to easier labor mobility, easier access for firms to customers and suppliers, and thus more opportunities for exchanging knowledge, skills, and information and obtaining knowledge spillovers. The knowledge spillover effect has always been the main concern of scholars at home and abroad. In recent years, the knowledge spillover effect has also begun to be emphasized in green technology innovation research. Scholars believe that the improvement of the overall capacity of technological innovation can also promote the enhancement of green technology innovation capacity. Sun et al. specialize in the study of the spatial spillover effect of transportation facilities on green technology innovation [9].

Based on this, we propose Hypothesis 2.

Hypothesis 2: Highway construction contributes to increasing industry and regional green productivity. It has a green technology innovation effect, which in turn affects regional green economic growth.

Methods and Data

Model Setting

In the research design aspect, the research on the transportation infrastructure economic growth effect and the related topic literature generally have three kinds of strategies. The first strategy is to adopt the mileage, the density of highways, or virtual variables such as "whether there is a highway connection" as the explanation variable [25]. The second strategy is to adopt the shortest travel time as a proxy variable for transport infrastructure [26, 27]. The third strategy uses market access as a proxy variable for transport infrastructure. Since Donaldson and Hornbeck proposed the concept of "market access" and its measurement methods, more and more literature has adopted this strategy [4]. For example, Herzog examined the impact of the national transportation network in the United States on regional economic growth [28]. Fretz et al. examined the impact of Swiss highways on city size and heterogeneity [29]. Baum-Snow et al. studied the effects of economic growth in the urban hinterland of highways [30]. This is because transport infrastructure development is more about expanding regional market access than mileage or density per se.

In this paper, we adopt market access based on the shortest travel time as a proxy variable for highways. Meanwhile, highway mileage and density are taken as alternative explanatory variables for the robustness test. The fixed effect model is used to examine the impact of highways on regional green productivity (GFTP). The specific regression model is shown in Equation (1):

$$ln(GFTP)_{it} = \lambda_0 + \lambda_1 \ln MA_{it} + \lambda_2 O_{it} + \Omega_i + \delta_t + u_{it} \quad (1)$$

In the regression model, $ln(GFTP)_{it}$ represents the natural logarithm of green total factor productivity for city i in year t. The primary variable of interest in this study is market access, denoted by $lnMA_{ct}$. The estimated coefficient for the core explanatory variable is represented by λ_1. A positive and statistically significant λ_1 suggests that the development of highway networks significantly promotes regional green economic growth. Conversely, if λ_1 is positive but not significant, it indicates that the construction of highway networks has a limited effect on regional green economic growth. O_{it} refers to regional-level control variables including investment in fixed assets, population size, total import and export trade, and foreign direct investment, among others. Additionally, δ_t captures the time effect, while δ_i represents the fixed effect specific to each city.

Variable Selection and Measurement

Independent Variable

In this study, we adhere to the prevailing approach in the literature, which employs green total factor productivity as a proxy variable for measuring green economic growth [31, 32]. Drawing from the production possibilities set that incorporates both desirable and undesirable outputs formulated by Hu et al., the measurement of green total factor productivity for cities in the Yangtze River Economic Belt is conducted using the Malmquist-Luenberger index based on the directional distance of non-radial SBM [2]. The assessment of green total factor productivity encompasses inputs of labor, capital, and energy while considering the augmentation of desirable outputs and the mitigation of non-desirable outputs. This approach aligns with the energy and environmental challenges that China faces during its process of economic development. The specific formula used for measurement is presented in Equation (2):

$$GML_t^{t+1} = \left[\frac{D_0^t(x^t,y^t,b^t,g^t)}{1+D_0^t(x^{t+1},y^{t+1},b^{t+1},g^{t+1})} \times \frac{D_0^{t+1}(x^t,y^t,b^t,g^t)}{1+D_0^{t+1}(x^{t+1},y^{t+1},b^{t+1},g^{t+1})}\right]^{\frac{1}{2}} \quad (2)$$

In this context, $D_0^t(x^t, y^t, b^t, g^t)$ represents the distance function in period t, which quantifies the disparity between the decision unit and the efficient production frontier. Here, D signifies the production unit, while x, y, d, and g denote the production inputs, desired outputs, non-desired outputs, and directional variables, respectively. If $GML_t^{t+1} > 1$, it signifies an improvement in green total factor productivity from period t to t+1. Conversely, if $GML_t^{t+1} >1$ is less than or equal to 1, it indicates a decline in green total factor productivity.

The measurement of green total factor productivity incorporates indicators for both inputs and outputs. In this study, the specific composition of indicators for inputs and outputs is determined based on the methodology proposed by Hu et al. while considering data availability [2].

The input indicators considered in this study are as follows: (1) labor input, represented by the number of employed individuals in each city; (2) capital input, calculated using the "perpetual inventory method" with the formula $k_{it} = k_{it-1}(1-\delta_{it}) + I_{it}/p_{it}$, where i denotes the city, t denotes the year, and k, I, and δ denote the capital stock, investment amount, and depreciation rate, respectively. These variables are deflated using the base year of 2005. Lastly, (3) energy consumption is measured by the amount of electricity utilized by the city throughout the year.

The output indicators comprise desired outputs, which are expressed as the gross domestic product (GDP) of each city adjusted to the base period of 2005. Additionally, undesirable outputs encompass wastewater emissions, sulfur dioxide (SO_2) emissions, and soot emissions.

Dependent Variable

Market access usually encompasses multiple forms, with the prevailing form commonly employed in the literature being:

$$MA_i = \sum_j M_j f(t_{ij}) \quad (3)$$

In the equations, MA_i represents the market access at origin i and M_i represents the characteristics of the target location, typically gauged by the market size denoted as GDP or population. $f(t_{ij})$ symbolizes the decay function, reflecting the generalized cost of travel from origin i to destination j. Here, t_{ij} represents the travel time, distance, or toll costs between i and j. The decay function quantifies the inverse relationship between the likelihood of traffic flow and economic activity between the two locations and the travel time, distance, or toll costs.

The primary distinction among various measures of market access pertains to the decay function and its parameter values, necessitating further research for determination. Given the attributes of the Yangtze River Economic Belt, characterized by its vastness and considerable travel duration, this paper adopts the commonly employed exponential decay function from the literature, specifically suitable for long-distance travel, namely:

$$f(t_{ij}) = e^{-\beta t_{ij}} \ (\beta \text{ is the decay function parameter}, \ \beta>0) \quad (4)$$

The exponential decay function is applied in the above equation, where the "iceberg cost" is represented as $\tau_{ij} = e^{\frac{\beta}{\theta}t_{ij}}$. This cost condition satisfies $\tau_{ij} = e^{\frac{\beta}{\theta}t_{ij}}>1$ and further increases with the passage of time. Consequently, $f(t_{ij}) = \tau_{ij}{}^{-\theta} = e^{-\beta t_{ij}}$. As previously mentioned, the target location's characteristic M_j, denoting the market size Y_j^r of the specific region, is substituted with GDP. Thus, the market access measurement formula employed in this study is:

$$MA_i = \sum_j M_j f(t_{ij}) = \sum_j \tau_{ij}{}^{-\theta} Y_j^r = \sum_j e^{-\beta t_{ij}} GDP \quad (5)$$

This paper adopts the approach proposed by Wang et al. to measure the value of the decay function parameter β [20]. The measurement involves constructing the origin-destination (O-D) matrix for highway traffic flow and travel time between cities, followed by assessing the market access influenced by the highway. The constructed OD_{ij} measurement model is as follows:

$$OD_{ij} = KM_i{}^{\alpha_i} M_j{}^{\alpha_j} f(t_{ij}) \quad (6)$$

In this context, OD_{ij} represents the traffic flow traveling through the highway from city i to city j, while

M_i and M_j denote the respective sizes of cities i and j. The decay function is denoted as $f(t_{ij})$, where t_{ij} represents the travel time between location i and destination j. Additionally, the scale factor is represented by k.

By substituting Equation (4) into Equation (6), the result is obtained.

$$OD_{ij} = KM_i^{\alpha_i} M_j^{\alpha_j} e^{-\beta t_{ij}} \quad (7)$$

By applying the logarithm function to both sides of Equation (7), i.e.,

$$ln\, OD_{ij} = ln\, K + \alpha_i\, ln\, M_i + \alpha_j\, ln\, M_j - \beta t_{ij} \quad (8)$$

We conducted annual regressions using ordinary least squares (OLS) on Eq. (8) to estimate the decay function parameter β for each year.

The formula for measuring the time t_{ij} in Eq. (8) is provided by Eq. (9)

$$t_{ij} = min(t_{is}^{Road} + t_{ss'}^{\mathrm{HW}} + t_{s'j}^{Road}),\ \ (s \neq s') \quad (9)$$

The formula for measuring the time t_{ij} in Eq. (8) is provided by Eq. (9), among them

$$t_{is}^{Road} = L_{is}/RoadV_{is} \quad (10)$$

$$t_{ss'}^{\mathrm{Hw}} = L_{ss'}/HwV_{ss'} \quad (11)$$

$$t_{s'j}^{Road} = L_{s'j}/RoadV_{s'j} \quad (12)$$

Equation (9) defines t_{ij} as the shortest total travel time from city *i* (where the municipal government is located) to city *j* (also with the municipal government), encompassing both general roads and highways. In Equation (10), L_{is}, $RoadV_{is}$, and t_{is}^{Road} represent the distance traveled, average speed, and time consumption, respectively, from city *i* to the closest highway import/export point s via the road network. Equation (11) describes Lss', $HwV_{ss'}$ and $t_{ss'}^{Hw}$ as the distance traveled, average highway speed, and time consumption, respectively, from the nearest highway import vehicle *s* in city *i* to the nearest highway import/export point *s'* in city *j* using the highway network. Furthermore, Equation (12) denotes $L_{s'j}$, $RoadV_{s'j}$ and $t_{s'j}^{Road}$ as the distance traveled, average speed, and time consumption, respectively, from the nearest highway import vehicle s in city i to the nearest highway import/export point s in city *j* via the road network. Lastly, Equation (13) describes $L_{s'j}$, $RoadV_{s'j}$ and $t_{s'j}^{Road}$ as the time consumed from the nearest highway import vehicle *s'* to the final destination city *j*, considering the distance traveled, average speed, and time consumption through the highway network.

This paper addresses the absence of inter-regional traffic flow vector data by converting each city's passenger traffic into vector data using city size (proxied by population) and the distance between cities. This transformation allows for the generation of the OD matrix. The gravitational coefficient between city i and city j is then calculated using equation (13).

$$k_{ij} = \frac{\sqrt{M_i} * \sqrt{M_j}}{d_{ij}} \quad (13)$$

The gravity coefficient, denoted as k_{ij}, incorporates the size and spatial distance between city *i* and city *j*. Here, M_i and M_j represent the sizes of city *i* and city *j*, respectively, while d_{ij} corresponds to the distance between city *i* and city *j*, specifically, the shortest travel time between their respective municipal governmental sites. Formula (14) utilizes the gravitational coefficient as a weight to compute the weighted average distribution of traffic flow from location i to other destinations.

$$OD_{ij_1} = kyl_i * \frac{k_{ij_1}}{k_{ij_1} + k_{ij_2} + k_{ij_3} \ldots\ldots k_{ij_n}}$$

$$OD_{ij_2} = kyl_i * \frac{k_{ij_2}}{k_{ij_1} + k_{ij_2} + k_{ij_3} \ldots\ldots k_{ij_n}}$$

$$\vdots$$

$$OD_{ij_n} = kyl_i * \frac{k_{ij_n}}{k_{ij_1} + k_{ij_2} + k_{ij_3} \ldots\ldots k_{ij_n}} \quad (14)$$

Here, OD_{ijn} represents the traffic flow between city *i* and city j_n, kyl_i denotes the traffic flow of city i, and k_{ijn} signifies the gravitational coefficient between city *i* and city j_n.

Using Eq. (5), market access MA_i can be measured. However, for the purpose of this paper, the focus lies on determining the path with the shortest travel time rather than the shortest distance. Consequently, it becomes essential to identify the path with the shortest passage time. For instance, when considering the recommended routes from Shanghai to Suzhou using the Baidu map, both Route 1 and Route 2 are available. While Route 2 covers a distance of approximately 97.4 kilometers and takes 2 hours and 7 minutes, Route 1 spans 99 kilometers, slightly longer than Route 2, yet it only takes 1 hour and 52 minutes. Hence, converting spatial distance into actual travel time is necessary to calculate the shortest route during the path determination process.

Initially, vector electronic maps of the highways spanning 2005 to 2019 were generated and aligned with the respective speed limits of each road segment. The ArcGIS map plug-in tool was employed to load the pertinent maps and draw the GIS layers of the most recent years' highways based on their routes, which were further calibrated utilizing the electronic maps available in the China Highway Network. Simultaneously, GPS navigation data from the Gaode map was leveraged to acquire the speed limit for each road section and associate it with the corresponding segment. Building upon these steps, the highway map was constructed using a deletion-based approach.

Secondly, the shortest travel time distance of the highway is computed. Upon establishing the GIS map of the highway and acquiring the speed limit data for each section, the OD-MATRIX method is employed to calculate the actual travel time between the government sites of each city. The calculation of the shortest travel time between cities A and B involves four steps: 1) constructing the road network between cities AB, encompassing the national highway, highway, and the connecting roads from the city government sites to the road network; 2) assigning the speed for each road section, with the speed limit set at 60 km/h for the national highway and connecting roads while varying for different sections of the highway; 3) based on the distance and speed of each road section, determining the actual travel time; 4) computing the shortest travel time path within city AB by considering the "time distance" of different road sections and obtaining the actual time distance.

The above methodology enables the measurement of the shortest travel time distance between two cities, facilitating the acquisition of market access data pertaining to highways.

Control Variables

Drawing from an extensive review of existing research literature, this study establishes a set of control variables, including population size, employment level, amount of foreign direct investment, number of granted patents, government financial expenditure, length of general highways, and length of general railroads. The relevant main variables are described in Table 1.

Variable Description

Data for this study was collected from 126 prefecture-level and higher administrative districts, spanning the period of 2005-2019. The required data sources include the China Urban Statistical Yearbook as well as provincial and municipal statistical yearbooks. Missing values were supplemented by referring to the statistical yearbooks of provinces, statistical bulletins of prefecture-level and higher administrative districts, and government work reports.

As there is a significant disparity in the magnitudes of different variables, the presence of heteroskedasticity can affect the empirical estimation results. To mitigate this impact, certain variables are first transformed using the natural logarithm before being included in the model. Table 2 displays the descriptive statistics for each regression variable after this transformation.

Results

Basic Results

This paper empirically examines the impact of highways on regional green economic growth using panel data from 126 prefecture-level and above cities in the Yangtze River Economic Belt. The data spans from 2005 to 2019. The explanatory variable is defined as urban market access, while the dependent variable is green total factor productivity. A fixed-effects model is adopted for regression analysis, and the results are presented in Table 3.

Column (1) of Table 3 presents the regression results of the explanatory variables in relation to the explanatory variables alone. The analysis reveals a significant positive correlation between the change in market access resulting from highways and the logarithm of

Table 1. Variable explanation.

Variable type	Variable	Symbol	Meaning
Dependent variables	Regional total factor productivity	GFTP	The overall green economy efficiency of the region
Independent variable	Regional market access	MA	Inter-city market access based on highways
Control variables	Permanent population	Population	The size of the resident population in each city
	Number of employed persons	Employee	The total number of employed people in each city in a whole year
	Investment in fixed assets	Finvest	Total fixed assets minus increase in fixed assets
	Opening up to the outside world	FDI	Foreign direct investment
	The proportion of government expenditure	Finance	The ratio of government expenditure to GDP
	Other modes of transportation-ordinary highways	Road	The total mileage of the general highway in each city
	Other modes of transportation-ordinary railway	Rail	The total mileage of ordinary railways in each city

Table 2. Statistical description.

Variable name	Observations	Maximum	Minimum	Average	Sdv.
ln_GTFP	1,890	0.058	-0.0407	0.009	0.029
ln_MA	1,890	13.750	4.680	12.980	0.910
ln_population	1,890	9.306	4.500	6.068	0.609
ln_finvest	1,890	19.020	12.74	15.910	1.105
ln_FDI	1,890	14.920	1.116	10.000	2.037
ln_finance	1,890	0.834	-4.583	-1.905	0.616
ln_employee	1,890	6.892	1.711	3.611	0.864
ln_road	1,890	11.704	6.5132	9.298	0.594
ln_rail	1,890	7.196	0	5.166	0.912

Table 3. Benchmark regression results.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	ln_GTFP	ln_GTFP	ln_GTFP	ln_GTFP	ln_GTFP	ln_GTFP	ln_GTFP	ln_GTFP
ln_MA	0.009***	0.008***	0.007***	0.008***	0.007***	0.006***	0.006***	0.006***
	(6.32)	(5.36)	(5.15)	(5.24)	(4.88)	(4.69)	(4.66)	(4.40)
ln_population		0.072***	0.069***	0.069***	0.060***	0.059***	0.059***	0.056***
		(16.05)	(15.47)	(15.47)	(14.04)	(13.90)	(13.92)	(13.35)
ln_finvest			0.020***	0.019***	0.017***	0.017***	0.016***	0.031***
			(6.97)	(6.91)	(6.44)	(6.24)	(6.12)	(9.60)
ln_finance				0.005**	0.006***	0.005***	0.005**	0.005**
				(2.39)	(2.62)	(2.62)	(2.51)	(2.23)
ln_employee					0.035***	0.035***	0.035***	0.040***
					(12.76)	(12.62)	(12.82)	(14.31)
ln_FDI						0.005***	0.005***	0.004***
						(3.82)	(3.97)	(3.55)
ln_road							0.019***	0.017***
							(2.92)	(2.66)
ln_rail								0.001***
								(3.04)
Constant	-0.105***	-0.518***	-0.779***	-0.765***	-0.787***	-0.777***	-0.775***	-1.007***
	(-5.90)	(-16.48)	(-15.96)	(-15.60)	(-16.89)	(-16.72)	(-16.72)	(-18.04)
Observation	1,890	1,890	1,890	1,890	1,890	1,890	1,890	1,890
R-squared	0.027	0.172	0.197	0.200	0.279	0.286	0.290	0.320
City FE	YES	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES	YES

Note: Heteroskedasticity robust t-statistics are stated in parentheses below point estimates. ***1%, **5%, and *10% significance levels.

GFTP. This correlation is statistically significant at the 1% confidence level, aligning with the findings of the general gravity model. Subsequently, columns (2)-(6) of Table 3 progressively introduce control variables. In column (6), all control variables are included, and the corresponding results are presented. The regression coefficient for the aforementioned explanatory variable indicates a positive relationship. Moreover, the output elasticity of the explanatory variable (*ln_MA*) with respect to the logarithm of GFTP is calculated as 0.006, which is significant at the 1% level. Hence, a 10% change in regional market access, brought about by the introduction of highways, is estimated to drive a 0.06% growth in regional GFTP. These findings underscore the significance of changes in regional market access facilitated by highway development for promoting regional green economic growth.

Robustness Test

To assess the robustness of the benchmark regression results, this paper employs three methods for the purpose of conducting robustness testing.

Firstly, the measure of green total factor productivity is modified, and the coefficients are subsequently re-estimated. The green total factor productivity of prefecture-level and above cities in the Yangtze River Economic Belt is measured in the benchmark regression using the non-radial SBM directional distance-based Malmquist-Luenberger index. The Slacks-based measure-Global Malmquist-Luenberger productivity index (SBM-GML) and Slacks-based measure-directional distance function (SBM-DDF) methods are employed to re-measure the green total factor productivity of cities in the Yangtze River Economic Belt [33-34]. The empirical test results are presented in Table 4. Columns (1)-(2) of Table 4 utilize the logarithm of green total factor productivity calculated by SBM-GML as one explanatory variable, along with the logarithm of highway market access as another explanatory variable. The coefficients of *ln_MA* remain significantly positive at the 1% confidence level. Columns (3)-(4) of Table 4 substitute the explanatory variables with the green total factor productivity calculated by SBM-DDF, and the obtained outcomes align with those of SBM-DDF. The outcomes regarding green total factor productivity demonstrate consistency with the benchmark regression results.

Subsequently, the explanatory variables are substituted with the number of highway miles and highway mileage density for regression analysis, and the obtained outcomes are presented in Table 5. In columns (1)-(2) of Table 5, when using the logarithm of GFTP as the explanatory variable and the logarithm of the number of highway miles as the explanatory variable, the coefficient of *ln_miles* exhibits a significant positive correlation at a confidence level of 1%. Thus, indicating a significant positive relationship between the number of highway miles and GFTP, implying that a larger highway network construction positively influences regional green economic growth. Subsequently, columns (3)-(4) of Table 5 substitute the explanatory variables from highway-induced market access with the logarithm of highway density (*ln_density*). The logarithm of GFTP remains the explanatory variable. The empirical results obtained align with the findings of the benchmark regression.

The benchmark regression utilizes a time window spanning from 2005 to 2019. In the robustness test, the time window is adjusted by excluding specific data periods: the first year, the first two years, the first three years, the last year, the second two years, and the last three years. Subsequently, a regression test is conducted, and the outcomes are presented in Table 6.

Table 4. Robustness tests: changing the explanatory variable measures.

	(1)	(2)	(3)	(4)
	ln_GTFP_ SBM-GML	ln_GTFP_ SBM-GML	ln_GTFP_ SBM-DDF	ln_GTFP_ SBM-DDF
ln_MA	0.011***	0.005**	0.018***	0.017**
	(6.53)	(2.13)	(4.06)	(2.40)
Constant	-0.140***	-0.120**	-0.236***	-0.313*
	(-6.69)	(-2.09)	(-4.10)	(-1.95)
Observation	1,890	1,890	1,890	1,890
R-squared	0.024	0.044	0.009	0.013
Control variable	NO	YES	NO	YES
City FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES

Note: Heteroskedasticity robust t-statistics are stated in parentheses below point estimates. ***1%, **5%, and *10% significance levels.

Table 5. Robustness tests: replacing explanatory variables.

	(1)	(2)	(3)	(4)
	ln_GTFP	ln_GTFP	ln_GTFP	ln_GTFP
ln_miles	0.022***	0.018***		
	(8.45)	(8.39)		
ln_density			0.026***	0.017***
			(9.83)	(7.52)
Constant	0.105***	-0.905***	-0.115***	-1.053***
	(8.91)	(-15.26)	(-8.95)	(-18.04)
Observation	1,890	1,890	1,890	1,890
R-squared	0.057	0.349	0.065	0.343
Control variable	NO	YES	NO	YES
City FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES

Note: Heteroskedasticity robust t-statistics are stated in parentheses below point estimates. ***1%, **5%, and *10% significance levels.

Table 6. Robustness tests: adjustment time window.

	2006-2019	2007-2019	2008-1029	2005-2018	2005-2017	2005-2016
	ln_GTFP	ln_GTFP	ln_GTFP	ln_GTFP	ln_GTFP	ln_GTFP
ln_MA	0.006***	0.006***	0.005***	0.005***	0.005***	0.005***
	(4.39)	(3.78)	(3.51)	(4.00)	(3.87)	(3.58)
Constant	-1.025***	-1.047***	-1.104***	-1.026***	-1.001***	-0.981***
	(-17.19)	(-16.23)	(-15.53)	(-17.79)	(-16.22)	(-15.00)
Observation	1764	1638	1512	1764	1638	1512
R-squared	0.320	0.325	0.331	0.320	0.322	0.322
City FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES

Note: Heteroskedasticity robust t-statistics are stated in parentheses below point estimates. ***1%, **5%, and *10% significance levels.

The robustness test not only confirms the robustness of the findings but also highlights a significantly larger coefficient for the impact of market access as an explanatory variable on green economic growth compared to the utilization of mileage and density as explanatory variables. It suggests that the existing literature underestimates the influence of highways on green economic growth by employing mileage and density as indicators for highway variables within specific regions.

Endogeneity Test

Due to the bidirectional relationship between the explanatory variables and the explained variables, potential endogeneity issues may arise, leading to biased estimates when relying solely on the Ordinary Least Squares (OLS) regression method with fixed effects. We employ the first-order lagged terms of the explanatory variables as instrumental variables and estimate the coefficients using the two-stage least squares method, great likelihood estimation with finite information, and systematic generalized moments estimation, respectively. Although there is a strong correlation between highway market access in the previous period and market access in the current period, it is important to note that the construction of transportation infrastructure in the previous period does not directly influence the current period's green economic growth. Thus, utilizing the lagged one-period of highway market

Table 7. Endogeneity test.

	2SLS	LIML	GMM
	ln_GTFP	ln_GTFP	ln_GTFP
ln_MA	0.024***	0.024***	0.024*
	(6.10)	(6.10)	(1.70)
Constant	-1.346***	-1.346***	-1.346***
	(-17.90)	(-17.90)	(-7.34)
Observation	1764	1764	1764
R-squared	0.270	0.270	0.270
First Stage F Statistics	2175		
Control variable	YES	YES	YES
City FE	YES	YES	YES
Year FE	YES	YES	YES

Note: Heteroskedasticity robust t-statistics are stated in parentheses below point estimates. ***1%, **5%, and *10% significance levels.

access as an instrumental variable is appropriate. Table 7 presents the results of the empirical analysis using instrumental variables, revealing an F-value of 2175 for the one-stage regression. This value exceeds the empirical threshold of an F-value greater than 10, suggesting the effectiveness of variable selection. Moreover, the signs and significance of the coefficients in the three regression models align closely with the prior empirical findings.

Heterogeneity Test

Cities are categorized into three groups: large, medium, and small cities, according to the size of the resident population in the city's municipal district. The division method takes quartiles for sample classification. Taking regional market access as the explanatory variable, the regression results are shown in Table 8. The coefficients of the explanatory variable *ln_MA* are all positive. This indicates that there is an obvious positive correlation between the changes in market access brought by highways and GFTP. The construction of highways has a significant role in promoting regional green economic growth. In comparison, market access has a greater impact on GFTP in large cities, followed by medium and small-sized cities.

Cities are divided into central cities and non-central cities according to their hierarchy. Central cities include provincial capitals, municipalities directly under the central government, and planned cities. Other cities are non-central cities. Uneven distribution of highway

Table 8. Heterogeneity test: subsample regression by city size.

	Large city	Medium city	Small city
	ln_GTFP	ln_GTFP	ln_GTFP
ln_MA	0.496***	0.484***	0.005***
	(23.34)	(92.69)	(3.71)
Constant	-5.920***	-5.820***	-0.976***
	(-39.89)	(-105.85)	(-16.00)
Observation	675	648	567
R-squared	0.677	0.660	0.387
Control variable	YES	YES	YES
City FE	YES	YES	YES
Year FE	YES	YES	YES

Note: Heteroskedasticity robust t-statistics are stated in parentheses below point estimates. ***1%, **5%, and *10% significance levels.

Table 9. Heterogeneity test: subsample regression by city class.

	Central city	Non-central city
	ln_GTFP	ln_GTFP
ln_MA	0.487***	0.005***
	(52.83)	(4.02)
Constant	-5.751***	-0.962***
	(-67.96)	(-16.32)
Observation	180	1710
R-squared	0.677	0.288
Control variable	YES	YES
City FE	YES	YES
Year FE	YES	YES

Note: Heteroskedasticity robust t-statistics are stated in parentheses below point estimates. ***1%, **5%, and *10% significance levels.

networks leads to unbalanced development among regions. Differences in the distribution of highways in different regions lead to differences in their green economic development. According to the division by city level, the impact of market access on urban green economic growth is empirically analyzed, and the results are shown in Table 9. It can be seen that the coefficients of the explanatory variables are consistently and significantly positive, and the coefficients of central cities are larger than those of non-central cities. This indicates that, compared with the central city, the enhancement of market access has a greater impact on the green economic growth of the central city.

Discussion

The establishment of highways diminishes overall transportation expenses, encompassing both transportation costs and time costs. This reduction becomes evident through alterations in market accessibility, fostering the emergence of green technology innovation effects that ultimately influence regional green economic growth. The objective of this section is to examine the mediating impact of the green technology innovation effect.

This study employs the number of patent applications for environmentally-related green technology inventions as an indicator to measure the output of green technological innovation. This choice offers the following three advantages: (1) The number of patent applications closely correlates with technological innovation. (2) The availability of data and minimal constraints by patent granting agencies make the number of patent applications a more accurate reflection of the level of green technological innovation compared to the number of patent grants. This approach reveals the state of green technological innovation within a specific region. (3) Since it takes time for a patent to be approved and authorized from application to authorization, the number of patent applications is more time-sensitive than the number of authorizations. This sensitivity proves beneficial in examining the green innovation activities within a region. Green technology patents are classified based on the standards set by the State Intellectual Property Office (SIPO), extracted from SIPO's patent database, and categorized according to the applicant's location.

This paper verifies the existence of the mediation effect in three steps: (1) Conducting a regression analysis of market access with the explanatory variable green economic growth and checking the significance of the regression coefficient. If it is significant, we proceed to the second and third steps; otherwise, we terminate the analysis. (2) Performing a regression analysis of market access with green technological innovation. A significant coefficient indicates that the opening of highways influences the effect of green technological innovation. (3) Putting the market access and mediating effect variables into the model and regressing them with the explanatory variable, green economic growth. By examining the significance of the regression coefficient, it can be determined whether the mediating effect is significant. If it is significant, the mediating effect is deemed significant; otherwise, the full mediating effect is considered not significant. Based on these steps, the mechanism validation model is formulated as follows:

Step 1: Examining the impact of highway market access on green economic growth.

$$lnGTFP_{it} = \beta_0 + \beta_1 MA_{it} + \beta_2 X_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (15)$$

Step 2: Investigating the impact of highway market access on the mediating variable, which is green technology innovation.

$$\ln intermediate\ variable_{it} = \beta_0 + \beta_1 MA_{it} + \beta_2 X_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (16)$$

Step 3: Putting both highway market access and mediating variables into the regression equation.

$$lnGTFP_{it_{it}} = \theta_0 + \theta_1 MA_{it} + \theta_2 intermediate\ variable_{it} + \theta_3 X_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (17)$$

To test the mediating effect, the initial step involves examining the relationship between highway market access and the mediating variable, green technology innovation, referred to as Equation (16). Subsequently, the mediating variable is incorporated into the basic regression model, resulting in a new regression Equation (17), and the resulting changes in the regression

Table 10. Mechanism tests.

	(1)	(2)	(3)
	ln_GTFP	*ln_patent*	*ln_GTFP*
ln_MA	0.006***	0.062**	0.006***
	(4.40)	(2.20)	(4.37)
ln_patent			0.004***
			(3.57)
Constant	-1.007***	-2.697**	-1.007***
	(-18.04)	(-2.28)	(-18.03)
Observation	1890	1890	1890
Sobel			-0.001**
			(-2.30)
R-squared	0.287	0.869	0.320
Control variable	YES	YES	YES
City FE	YES	YES	YES
Year FE	YES	YES	YES

Note: Heteroskedasticity robust t-statistics are stated in parentheses below point estimates. ***1%, **5%, and *10% significance levels.

coefficients are analyzed. If the coefficients α_1, β_1, θ_1 and θ_2 are statistically significant and θ_1 exhibits a decrease in magnitude or lose significance compared to α_1, it indicates a partial mediation effect. Conversely, if θ_1 is no longer statistically significant, it suggests a full mediation effect.

The mediation effect measurement model incorporates mediating variables to further examine the relationship between market access, mediating variables, and green economic growth, utilizing the shortest highway travel time as a basis. The empirical results of the mediation effect model are presented in Table 10. Upon observing the regression results, it is evident that the coefficients of market access in column (2) are all significantly positive. Furthermore, the coefficients of the main explanatory variables in column (3) exhibit a decrease in magnitude compared to column (1).

Moreover, it is evident that the introduction of green technology innovation in column (3) significantly contributes to green economic growth. This finding indicates the presence of a partial mediating effect, demonstrating that the impact of the highway on green economic growth is manifested through the effect of green technology innovation. The core of the mediation effect test lies in examining the product of coefficients. In this study, the Sobel method is employed to test the estimation results using the product coefficient test method. The analysis reveals that the Sobel test yields a P-value of less than 0.1, providing evidence for the establishment of the mediation effect.

Conclusion and Insight

Highways are an important modern transportation mode, and their role in the allocation of green economic growth and resources in the Yangtze River Economic Belt has a significant impact. This paper finds that, first, the parameters of the decay function and the market access of the Yangtze River Economic Belt are measured in this paper using Chinese highway data. Market access reflects changes in regional market scope and market size due to highway construction. Second, changes in market access based on highway construction have a significant positive impact on green economic growth in the Yangtze River Economic Belt. Third, cities are regressed into subsamples according to two criteria: population size and city class. The results show that highway market access has the largest effect in large-scale cities, followed by medium-sized cities, and has the smallest effect on small-sized cities. In addition, the role of market access changes is greater in central cities than in non-central cities. Fourth, the impact mechanism of highway construction on green economic growth is discussed. This paper utilizes the mediation effect model to verify the mediation effect of green technology innovation. The results show that green technology innovation has a partial mediating effect. This indicates that the impact of the highway on regional green economic growth can be realized by promoting regional green technology innovation.

Based on the research findings, this paper puts forward the following policy recommendations on optimizing highway planning and management and the green economic development of the Yangtze River Economic Belt: First, highlight the key points and optimize the planning layout of highways in the Yangtze River Economic Belt. Highlight the construction of highways in metropolitan areas such as municipalities, provincial capitals, planned cities, and megacities in the Yangtze River Economic Belt. Through the construction of the highway network, a reasonable division of labor among various cities in the Yangtze River Economic Belt will be formed, which can not only improve the efficiency of resource spatial allocation, but also be conducive to green economic growth. Second, vigorously promote the reform and innovation of highway management mechanisms. Carry out top-level design at the national level. According to the differences in traffic volume by region, road section, and time period, introduce highway charging methods and charging standards. Promote the electronic, non-stop express toll collection system. Third, accelerate green technology innovation and overflow in the Yangtze River Economic Belt. Relying on the transportation advantages of the highway network, increases the promotion of cross-regional spillover of green technology and green knowledge, and supports the cross-regional mobility of various types of research and development personnel.

There are some shortcomings in this paper, which are highlighted in two aspects: First, in the measurement of indicators, the data on traffic flow between regions in the Yangtze River Economic Belt are not directly obtained, but are estimated based on the gravity model. At the same time, changes in parameters such as commuting costs were not analyzed. Secondly, in terms of empirical research, for the highway data, this paper takes the mileage and opening time of each region, but not the number and range of highway imports and exports in each region. It is highway import and export that really has an impact on regional green economic growth, which restricts the depth of analysis in this paper. In future research, we should further introduce more independent variables according to the highway accessibility characteristics to more accurately reflect the uniqueness of the highway, and on the other hand, we should distinguish the heterogeneous regions from multiple perspectives and analyze the sensitivity of their responses to the highway accessibility characteristics, such as the time distance and the time cost, combined with the heterogeneous industries and heterogeneous enterprises, so as to more deeply discuss the micro-mechanisms of the highway influencing the regional green economic growth. The micro-mechanism of the highway affecting regional green economic growth is explored more deeply. In terms of empirical analysis, it is based on the impact of highway import and export on regional green economic growth at a smaller spatial scale and the degree of spatial attenuation, so as to make the conclusions of the study more precise.

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Conflict of Interest

The authors declare no conflict of interest.

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