

Article

Does the Opening of High-Speed Railway Lines Reduce the Carbon Intensity of China's Resource-Based Cities?

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Abstract: The carbon intensity of China's resource-based cities (RBCs) is much higher than the national average due to their relatively intensive mode of development. Low carbon transformation of RBCs is an important way to achieve the goal of reaching the carbon emissions peak in 2030. Based on the panel data from 116 RBCs in China from 2003 to 2018, this study takes the opening of high-speed railway (HSR) lines as a quasi-experiment, using a time-varying difference-in-difference (DID) model to empirically evaluate the impact of an HSR line on reducing the carbon intensity of RBCs. The results show that the opening of an HSR line can reduce the carbon intensity of RBCs, and this was still true after considering the possibility of problems with endogenous selection bias and after applying the relevant robustness tests. The opening of an HSR line is found to have a significant reducing effect on the carbon intensity of different types of RBC, and the decline in the carbon intensity of coal-based cities is found to be the greatest. Promoting migration of RBCs with HSR lines is found to be an effective intermediary way of reducing their carbon intensity.

Keywords: resource-based city; high-speed railway; carbon intensity; difference-in-difference method; China



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1. Introduction

Resource-based cities (RBCs) are cities with natural resources such as forests and minerals, and forestry or extraction and processing of minerals are their leading industries. As an important strategic base of energy resources, RBCs play an important role in China's economic growth. At present, China's carbon emissions are among the highest in the world. At the 75th United Nations conference in September 2020, the Chinese government promised to strive to achieve peak carbon emissions by 2030 and to meet a target of carbon neutrality before 2060. In December of the same year, at the Climate Ambition Summit, China committed to a reduction in carbon dioxide emissions per unit of GDP by 65% from 2005. This reduction in carbon intensity will be a binding target for Chinese provinces and cities.

At the same time, China's transportation infrastructure continues to develop rapidly, and the speed and scale of high-speed railway (HSR) construction in particular has attracted worldwide attention. Since the Beijing–Tianjin intercity railway was opened to traffic in 2008, during the 13th five-year plan, the operating mileage of HSR lines in China increased from 1980 km to 37,900 km, ranking the highest in the world. The medium- and long-term HSR network planning approved by the State Council in 2016 aims to build a “eight vertical and eight horizontal” main HSR lines, striving to realize internal and external interconnection, smooth regional connections, HSR connections between provincial capitals, rapid city access, and basic county coverage by 2030 [1].

The opening of HSR lines can significantly improve the accessibility of cities and accelerate the flow of production factors. On the one hand, it may have positive technological impacts on the production efficiency of manufacturing and service sectors, thus effectively promoting the economic growth of RBCs [2]; on the other hand, ongoing investment in transport infrastructure will have a negative impact on the environment [3,4]. However, the opening of an HSR line will reduce greenhouse gas emissions when compared to the development of other modes of transport [5]. This indicates that the opening of an HSR line will have an impact on both the regional economy and the environment.

According to the National Sustainable Development Plan for Resource-based Cities (2013–2020) issued by the Chinese government in 2013, RBCs are divided into four types: growth, mature, recessive, and regenerative. Of the 126 prefecture-level administrative units categorized as RBCs, 20 are in the growth stage and 66 are in the mature stage. Recessive RBCs tend to be resource exhausted, and 24 fall into this category. Regenerative RBCs are those that are essentially no longer dependent on resources, and the remaining 16 fall into this category.

As noted, RBCs have as their leading industries forestry and the mining and processing of natural resources, including fossil fuels which are closely related to carbon emissions. Therefore, RBCs have become the main sources of carbon emissions in China. As the resources in existing RBCs are in different stages of development, the attention paid to them usually focuses on the evaluation of resource-utilization efficiency [6–8] and the influences of industrial structure and policy and the motivation of officials [9–12]. To date, there has been little research into the impact of HSR lines on the carbon intensity of different types of RBCs from the perspective of transportation. To fill in this gap, we propose three research questions in linear logic. First, does the HSR line have positive impact on the reduction of carbon intensity of RBCs? Second, since there are different types of RBCs, is the impact of carbon intensity reduction the same for different RBCs? Third, if there is a positive impact, how does the HSR reduce the carbon intensity of RBCs?

By answering these questions, this paper will make contributions in the following aspects. (1) In terms of research theme, this paper will bring new perspective to the socio-economic effects of HSR on RBCs by investigating the relationship between HSR and carbon intensity, and exploring whether the opening of HSR can reduce the carbon intensity. (2) In terms of theoretical extension, this paper will further our understanding on the environmental effects of transportation with a focus on the factor flows promoted by HSR. (3) In terms of method improvement, this paper will take whether to open HSR as a “quasi natural experiment” and use DID model to empirically investigate the impact of HSR on carbon intensity of RBC, so as to reduce the estimation error caused by endogenous problems, and improve the accuracy and credibility of the research results.

The rest of the paper is structured as follows. Section 2 reviews the relevant literature, Section 3 introduces the DID method for examining the effect of HSR lines on the carbon intensity of China’s RBCs, and an empirical analysis of the impact of HSR lines on the carbon intensity of China’s RBCs is conducted in Section 4. Section 5 presents discussions and Section 6 provides a summary of the research results and puts forward the policy suggestions for potential HSR construction to reduce the carbon intensity of China’s RBCs.

2. Literature Review

In recent years, the Chinese government has responded to global climate change by taking various carbon emission-reduction measures. The long-term high-intensity development and efficiency management of RBCs mean that they generally face problems such as resource exhaustion, environmental destruction, and weak economic growth [13]. These problems need to be solved under the guidance of the government [10]. Research on the economic transformation of RBCs has been undertaken to evaluate their socio-economic and ecological environmental development [14,15] and their resource-utilization efficiency [6,16,17], including development mechanisms and influencing factors [13,18,19]. Previous research has focused on the factors affecting the efficiency of resource utilization

in RBCs and has mainly examined the industrial structure of the cities themselves. In particular, it has been found that the proportion of tertiary industry, such as transport, in RBCs is positively correlated with resource-utilization efficiency [16] and financial expenditure is negatively correlated with resource-utilization efficiency [19].

The Chinese proverb “if you want to be rich, build roads first” explains the internal relationship between transportation infrastructure and regional economic development. Relevant studies on the relationships and internal mechanisms between regional transportation infrastructure and economic growth show that the transportation infrastructure can promote economic growth [20–22]. In addition, transportation can also have environmental impacts [23–27]. Chakraborty [28] used an environmental justice index to evaluate the impact of transportation improvement projects in the US. Walmsley et al. [29] conducted carbon-emission pinch analysis on the transport sector in New Zealand. Guo et al. [30] studied green transport schemes using nonlinear programming. Peeters et al. [31] found that, among the transport modes of European tourism, air travel has the highest greenhouse gas emissions. Gagatsi et al. [32] explored the potential of using electric ferries in Europe to minimize CO₂ emissions and air pollution. Li et al. [33] believe that in the fast-track transportation project life cycle, the construction phase has the highest environmental impact. Ge et al. [34] found that the traffic in the North China Plain is the main source of daytime air pollution in Beijing. Kishimoto et al. [35] thought that stringent road-transport emission standards play a significant role in supporting China’s air quality and climate-change mitigation goals. By evaluating the coordinated economic, social, and environmental development of four municipalities in China from 2004 to 2015, Sun and Cui [36] considered that large cities should give priority to the development of public transport and its supporting facilities.

As one of the important transportation modes for travel between regions, HSR lines play a role in boosting regional economic growth through investment [4]. In particular, for cities with a high degree of industrialization and strong labor use in service industries, the economic effect of opening an HSR line is more obvious [37]. For an RBC, the opening of an HSR line not only strengthens external contact but also improves the location of the RBC to a certain extent, speeding up the inflow of capital, reducing the cost of the flow of innovation elements such as human talent, and speeding up the dissemination of innovation elements such as knowledge [38,39]. Of course, the inflow of these production factors will inevitably have an impact on a city’s resource consumption and pollution emissions. For example, Chen believes that China’s HSR investment has resulted in huge economic effects but has also had significant effects on carbon emissions [39]. Song et al. used a non-radial data envelopment analysis model to calculate the environmental efficiency of 30 provinces in China and found that railways are the most environmentally friendly mode of transportation, suggesting that the government should redirect highway investment to the construction of HSR lines [40]. Chang et al. calculated that the operation of HSRs could reduce greenhouse gas emissions [5]. Using a DID model, Yang et al. considered that the environmental impact on different cities in China of opening HSR lines is heterogeneous [41]. Due to the “siphon effect” of big cities, the pollution-reduction effect of HSR lines is more significant in areas with large scales, high levels of economic development, and rich human resources.

Based on previous analysis, we propose three hypotheses below:

Hypothesis 1 (H1). *After the opening of HSR line, the carbon intensity of HSR RBCs will decrease faster than that of the non-HSR RBCs.*

Hypothesis 2 (H2). *The opening of HSR line will promote the population flow and accelerate knowledge flow, which will increase the innovation level and then have an effect on reducing carbon intensity.*

Hypothesis 3 (H3). *The effect of carbon intensity reduction due to the opening of HSR line will differ across different types of RBCs.*

To summarize, previous studies relating to RBCs have paid more attention to the evaluation of resource-utilization efficiency and the social and economic factors of the city itself, and there has been a lack of analysis of the impact of HSR lines on RBCs from the perspective of location improvement. As noted, RBCs are major areas of carbon emissions, but the existing literature has not examined the impact of HSR lines on different types of RBCs. To bridge this gap, this study calculated the carbon intensity of 116 RBCs in China and then used a DID model to analyze the impact of HSR line opening on the carbon intensity of different types of RBCs. The results have important practical significance for China's HSR construction program and the national goal of reaching peak carbon emissions in 2030 and reducing carbon intensity by 65% compared with 2005 level.

3. Materials and Methods

3.1. Carbon Emissions of Chinese RBCs and Uncertainty Analysis

Chinese provincial energy-related CO₂ emissions (i.e., emissions from fossil fuel combustion) are usually calculated according to the Intergovernmental Panel on Climate Change guidelines [42]. The amounts of CO₂ emissions (CE) are determined by each activity (AD) multiplied by net calorific value (NCV), an emission factor (EF), and oxygenation efficiency (O):

$$CE_{ji}^p = AD_{ji}^p \times NCV_j \times EF_j \times O_{ji}, \quad (1)$$

where CE_{ji}^p and AD_{ji}^p refer to CO₂ emissions and fossil fuel consumption by the corresponding (p) provincial energy types (j) and sectors (i) and is the NCV_j , EF_j , and O_{ji} are their corresponding parameters [43]. Since there is a lack of detailed data of fossil energy consumption for Chinese prefecture-level cities, in this study, provincial administrative units were used to calculate the energy consumption from four industrial sectors: primary industry ($i = 1$), secondary industry ($i = 2$), tertiary industry ($i = 3$), and residents' daily lives ($i = 4$). The CO₂ emissions from fossil fuel consumption for these four sectors in RBC m were calculated according to:

$$CE_{j1}^{m \in p} = A^m \cdot CE_{j1}^p, \quad (2)$$

$$CE_{j2}^{m \in p} = B^m \cdot CE_{j2}^p, \quad (3)$$

$$CE_{j3}^{m \in p} = C^m \cdot \gamma \cdot CE_{j3}^p, \quad (4)$$

$$CE_{j4}^{m \in p} = D^m \cdot CE_{j4}^p, \quad (5)$$

where A^m , B^m , C^m , γ , and D^m are individual weighting factors.

As CO₂ emissions mainly come from industry and transportation, the weighting factors were allocated according to the data available in the China City Statistical Yearbook and China Provincial Statistical Yearbook: A^m is the proportion of the added value of primary industry in RBC m in province p ; B^m is the proportion of industrial electricity consumption of RBC m in province p ; γ is the proportion of the added value of the tertiary industry of RBC m in province p ; $C^m = \rho^m / \sum \rho^m$, in which $\rho^m = (b^m \cdot \tau_b + c^m \cdot \tau_c) \cdot \omega^m$, b^m and c^m are the numbers of urban buses and taxis, respectively, with reference to literature [44], τ_b and τ_c are the corresponding carbon emission per unit distance, and ω^m is the space radius of city m ; D^m uses the proportion of the total population of city m in the total population of the province. Since A^m , B^m , and, γ , and D^m are determined according to published statistical data and ρ^m is generated from the actual mileage of all means of transportation in city m due to the lack of published data on carbon emissions, an uncertainty estimation is made here. According to the Monte Carlo simulation method, $\tau^m \pm 15\% \delta$, $\delta \sim N(0, 1)$ of was set for each prefecture-level city, and the variation range of carbon emissions of all provinces m caused by changing the carbon emissions in p was within 5% (Table 1). It should be noted that carbon-emission estimation methods represented by Equations (2)–(5)

did not cause dramatic changes in any of the provinces of China, and the estimation results can therefore be considered to be stable.

Table 1. Changes in carbon-emission estimations of whole provinces resulting from changes in the individual coefficients for resource-based cities (RBCs).

Province	Variation	Province	Variation	Province	Variation
Hebei	±0.62%	Fujian	±1.71%	Sichuan	±3.03%
Shanxi	±0.85%	Jiangxi	±1.51%	Guizhou	±4.10%
Inner Mongolia	±0.83%	Shandong	±1.07%	Yunnan	±2.62%
Liaoning	±1.51%	Henan	±1.46%	Tibet	±1.01%
Jilin	±1.30%	Hubei	±2.86%	Shaanxi	±1.57%
Heilongjiang	±1.92%	Hunan	±3.26%	Gansu	±1.45%
Jiangsu	±0.99%	Guangdong	±2.61%	Qinghai	±2.66%
Zhejiang	±1.68%	Guangxi	±1.59%	Ningxia	±0.41%
Anhui	±1.22%	Hainan	±3.12%	Xinjiang	±1.01%

3.2. Effects of HSR Lines on the Carbon Intensity of Chinese RBCs

This paper mainly studies the impact of HSR construction on the upgrading of RBCs' industrial structure. We assume that exogenous factors are basically stable. After the opening of HSR, the decline of carbon intensity mainly comes from two aspects: one is the effect caused by natural growth or economic trend change over time, namely "time trend effect"; the other is the policy effect caused by the opening of HSR, namely "net policy effect", which is the HSR opening effect and what we want to estimate in this paper. In order to estimate the "net policy effect", we need to exclude time trend effect from the total effect. The opening of an HSR in China separate the RBCs into two groups: one is the RBCs which have HSR stations, which we take as the "treated group"; the other is RBCs have no HSR stations, which is the "control group". The DID model can effectively separate the time trend effect and policy effect. Specifically, CI_{it}^0 and CI_{it}^1 represent carbon intensity of RBC i before and after opening of an HSR, $HSR_i \cdot Open_{it} = 1$ represents RBC i has opened HSR at year t , $HSR_i \cdot Open_{it} = 0$ represents RBC i did not open an HSR at year t . Then the causal effect of HSR on carbon intensity of RBCs can be represented as: $E\{CI_{it}^1 - CI_{it}^0 | HSR_i \cdot Open_{it} = 1\} = E\{CI_{it}^1 | HSR_i \cdot Open_{it} = 1\} - E\{CI_{it}^0 | HSR_i \cdot Open_{it} = 1\}$. We can evaluate this effect by using time-varying DID model. The baseline model was set as:

$$CI_{it} = \beta_0 + \beta_1 HSR_i \cdot open_{it} + \kappa_j \sum X_{jit} + \lambda_i + \mu_t + \theta_{it}, \quad (6)$$

where: CI_{it} is the explained variable for the yearly carbon intensity of city i in year t ; HSR_i is a dummy variable indicating the presence of an HSR line in a city, taking a value of 1 for RBCs opened an HSR line and 0 for RBCs do not open an HSR line; $open_{it}$ is a dummy variable indicating the period t that the HSR line has been in service in city i —the interaction of HSR_i and $open_{it}$ captures the treatment effect of the HSR line; X_{jit} represents control variable j with corresponding period t and city i ; β_0 is a constant term; β_1 is the coefficient of the explanatory variable and also the impact of HSR on carbon intensity; κ_j represents a coefficient for each control variable; λ_i and μ_t control for city-fixed and year-fixed effects, respectively; and θ_{it} is an error term.

3.3. Data Sources

In 2013, the National Sustainable Development Plan for Resource-Based Cities (2013–2020) [45] issued by the State Council of China identified 262 RBCs, from which 116 prefecture-level cities were selected along with balancing panel data for 116 cities from 2003 to 2018 to estimate the functions of carbon intensity of Chinese RBCs. Hence, the dataset is characterized by a relatively brief period of 16 years and a relatively large unit of 116 cities. In this study, the Qinhuangdao–Shenyang HSR line, which opened in 2003 [1], is the first Chinese HSR line to ensure an adequate sample size. Traffic information regarding the HSR

lines of RBCs was obtained from the website of the China National Railway Group. Chinese provincial CO₂ emissions accounting data related to fossil-fuel energy were taken from the China Energy Statistical Yearbook (2004–2019). The RBCs' CO₂ emission-related data were taken from the China City Statistical Yearbook (2004–2019) and the related Chinese Provincial Statistical Yearbook (2004–2019). This study calculated the carbon intensity of a city according to the constant price index of that city in 2003.

Four control variables (innovation level, openness level, financial self-sufficiency rate, and industrial structure) were used. The innovation level is the number of patent applications per 10,000 people. The openness level is the ratio of the actual utilization of foreign capital to GDP. The financial self-sufficiency rate is the ratio of a city's fiscal revenue to its fiscal expenditure. The industrial structure is the value added by a city's secondary industry as a fraction of GDP. Data relating to control variables were also taken from the China City Statistical Yearbook (2004–2019). The migration data comes from the China City Statistical Yearbook (2004–2019), Chinese provincial Statistical Yearbook (2004–2019) and China economic database website (<http://www.ceicdata.com/zh-hans/countries/china>, accessed on 20 January 2021).

Equation (6) requires the use of a software tool to solve the problem of endogenous selection bias regarding an HSR opening, and to this end, this paper introduces the average geographical gradient of RBCs as calculated using ArcGIS 10.0. In addition, in 2003–2018, the administrative divisions of some RBCs were renamed and adjusted, including Longnan prefecture-level city in Gansu Province, Lincang prefecture-level city in Yunnan Province, and Simao prefecture-level city in Yunnan Province. The renaming of a prefecture-level city did not affect the statistical scope of the data relating to its territorial unit. Missing data in some years were interpolated and supplemented. Descriptive statistics regarding explanatory and control variables are shown in Table 2.

Table 2. Descriptive variable statistics.

Variable	Definition	Obs.	Mean	Std. Dev.	Min	Max
CI	Carbon intensity	1856	0.443	0.581	0.016	6.929
In	Innovation level	1856	0.251	0.583	0.001	9.392
Op	Openness level	1856	0.107	0.149	0.000	1.548
Fi	Financial self-sufficiency	1856	0.425	0.182	0.055	1.116
Is	Industrial structure	1856	0.502	0.124	0.090	0.910
Te	Terrain slope	1856	2.608	2.047	0.040	11.820
M	Migration	1856	41.326	294.279	0.000	10719.080

4. Results

4.1. Temporal and Spatial Distributions of RBCs in China

Among the 116 examined RBCs, there were 15 in the growth stage, 63 in the mature stage, 23 were recessive, and 15 were regenerative. Six were forest industry-type cities, seven were oil and gas-type cities, 30 were metal-type cities, 13 were non-metallic-mineral type cities, and 60 were coal cities (Figure 1). Of the 116 RBCs, 64 had opened HSRs by 2018. Among the 15 growth RBCs, five had opened HSR lines, as indicated by the notation 15 (5). These figures were 63 (40) for mature cities, 23 (10) for recessive cities, and 15 (9) for regenerative cities. It can be seen that more than half of the mature and regenerative cities had opened HSR lines, specifically 63.5% and 60.0%, respectively. Furthermore, from the perspective of resource and mineral types, there were 6 (2) forest industrial cities, 7 (3) oil and gas cities, 30 (19) metal-mining cities, 13 (8) non-metallic-mineral mining cities, and 60 (32) coal-mining cities. More than half of metal-mining cities had opened HSR lines, and the figures were 61.5% for non-metallic-mineral mining cities and 53.3% for coal-mining cities, respectively. According to the types of RBCs in different development stages, the number of mature RBCs was the largest, accounting for 62.5%. In terms of resource and mineral types, the number of coal RBCs was the largest, accounting for 50.0%. By 2018, 64

out of 116 RBCs had opened HSR lines, a rate of 55.2%. The distribution of these new HSR routes is shown in Figure 2.

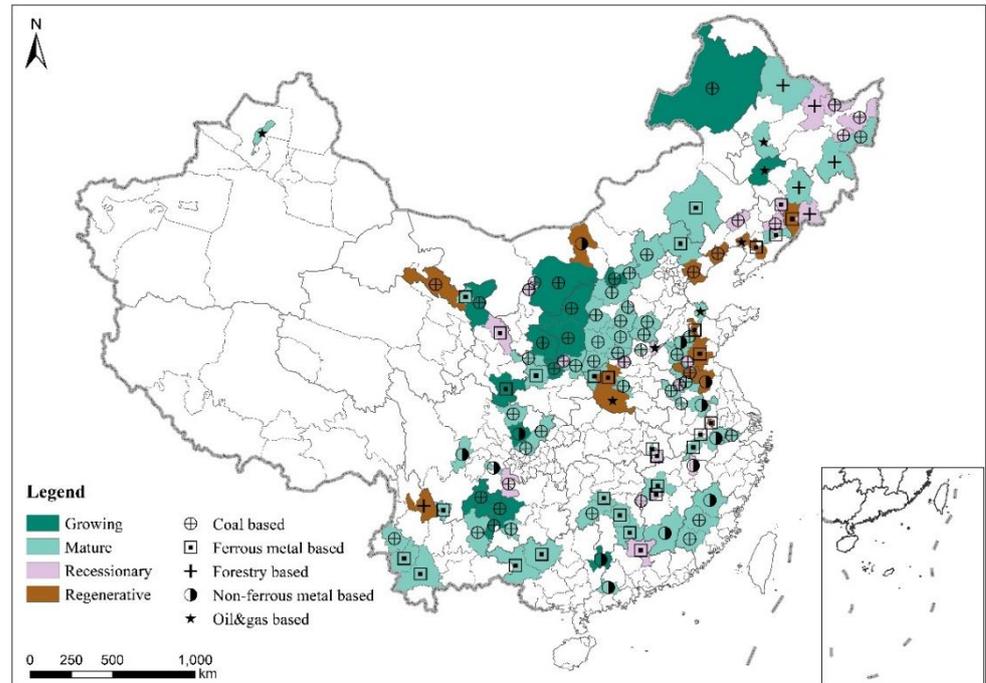


Figure 1. The locations of 116 RBCs in China.

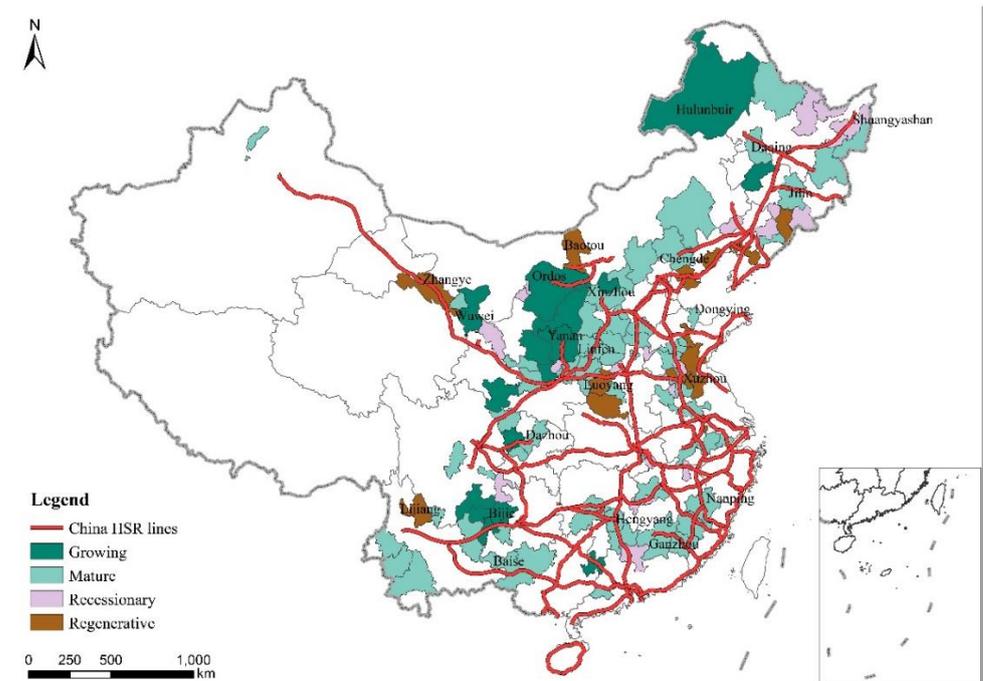


Figure 2. Distribution of new HSR routes.

During 2003–2018, the average carbon intensity of China’s RBCs decreased from 0.595 T/10³ yuan in 2003 to 0.499 T/10³ yuan in 2008. This continued to decline to 0.374 T/10³ yuan in 2013, dropping to 0.283 T/10³ yuan in 2018, a decline of 52.4%. The carbon intensity of RBCs showed a general downward trend. From the perspective of spatial distribution,

there were 12 RBCs with a carbon intensity greater than $1.0 \text{ T}/10^3 \text{ yuan}$ in 2003, among which Wuhai ($6.929 \text{ T}/10^3 \text{ yuan}$), Shizuishan ($4.147 \text{ T}/10^3 \text{ yuan}$), Tongchuan ($3.146 \text{ T}/10^3 \text{ yuan}$), Baotou ($3.098 \text{ T}/10^3 \text{ yuan}$), and Yangquan ($2.679 \text{ T}/10^3 \text{ yuan}$) had intensities of greater than $2.0 \text{ T}/10^3 \text{ yuan}$. In 2008, there were eight RBCs with a carbon intensity of more than $1.0 \text{ T}/10^3 \text{ yuan}$, among which four were RBCs with a carbon intensity of more than $2.0 \text{ T}/10^3 \text{ yuan}$: Wuhai ($5.371 \text{ T}/10^3 \text{ yuan}$), Shizuishan ($3.330 \text{ T}/10^3 \text{ yuan}$), Tongchuan ($3.254 \text{ T}/10^3 \text{ yuan}$), and Yangquan ($2.036 \text{ T}/10^3 \text{ yuan}$). In 2013, there were seven RBCs with a carbon intensity greater than $1.0 \text{ T}/10^3 \text{ yuan}$, among which Wuhai ($2.894 \text{ T}/10^3 \text{ yuan}$) and Yangquan ($2.065 \text{ T}/10^3 \text{ yuan}$) were the only RBCs with carbon intensities greater than $2.0 \text{ T}/10^3 \text{ yuan}$. By 2018, all the RBCs with carbon intensities greater than $1.0 \text{ T}/10^3 \text{ yuan}$ were in Shanxi Province, including Xinzhou ($1.497 \text{ T}/10^3 \text{ yuan}$), Lvliang ($1.427 \text{ T}/10^3 \text{ yuan}$), Yuncheng ($1.168 \text{ T}/10^3 \text{ yuan}$), and Jinzhong ($1.056 \text{ T}/10^3 \text{ yuan}$). These spatial and temporal patterns of carbon intensity are illustrated in Figure 3.

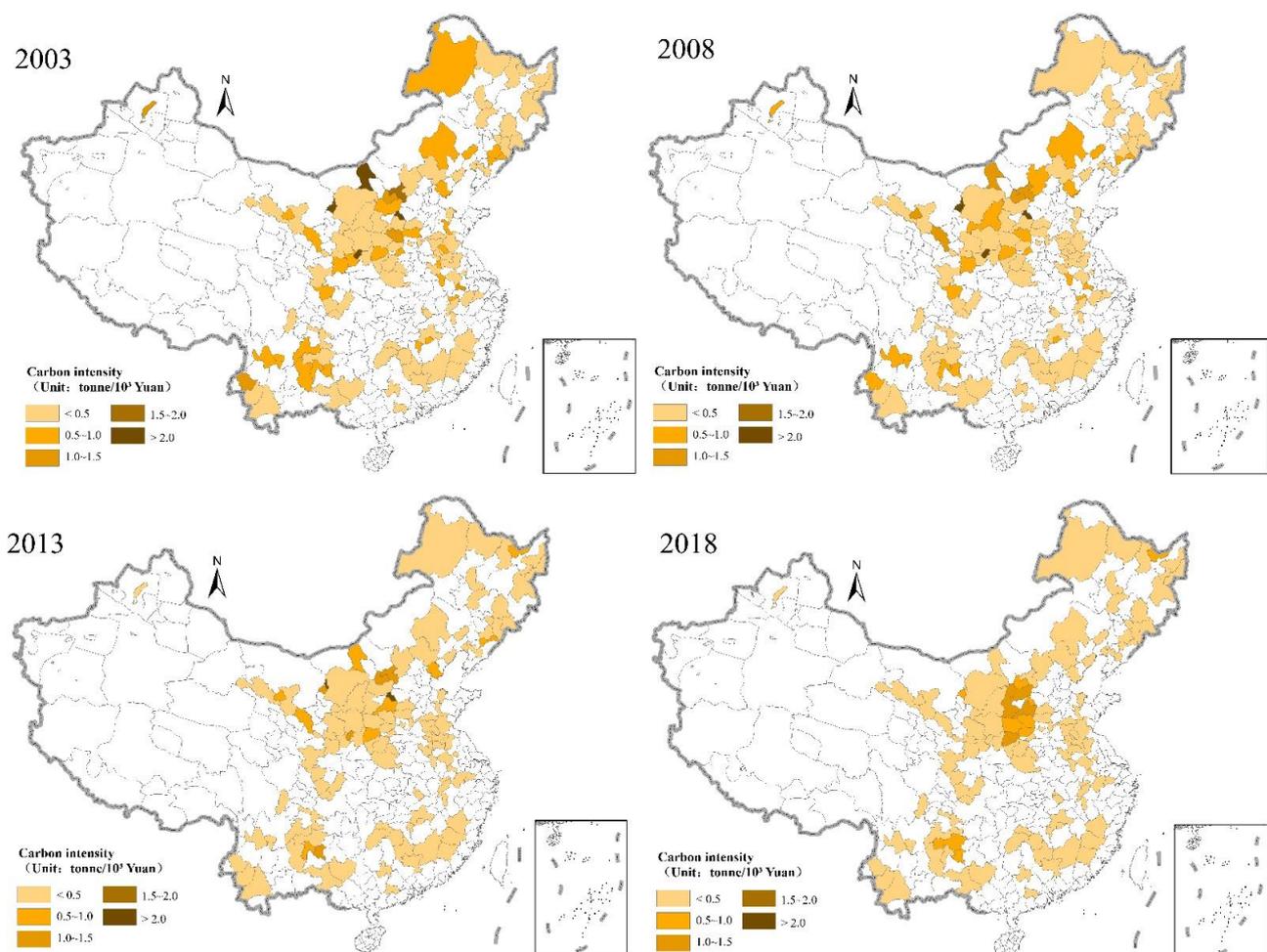


Figure 3. Spatial and temporal patterns of carbon intensity of 116 RBCs in China (unit: $\text{ton}/10^3 \text{ yuan}$).

The cities with high carbon intensity are mainly distributed in recessive RBCs (Wuhai, Shizuishan, and Tongchuan) and mature RBCs (Datong and Yangquan). Because the resource industries of these RBCs are in the declining and mature development stages, their economic growth is highly dependent on that industry, and their carbon intensity is generally high. As coal is the main source of carbon emissions in China, cities with high carbon intensity are mainly distributed in coal RBCs (Wuhai, Shizuishan, Tongchuan, Datong, Yangquan, Xinzhou, Lvliang, Jinzhong, and Yuncheng).

4.2. Baseline Results of Time-Varying DID Estimation

Because the opening times of the HSR lines in each city were not the same, the periods before and after the opening times in different cities in a given year were also different. For DID estimation, a parallel trend test is needed to ensure the reliability of the difference before and after the opening of an HSR line. Regression results were calculated using the equation:

$$CI_{it} = \alpha_0 + \sum_{j=-T}^T \varphi_j \cdot HSR_i \cdot open_{it-j} + \lambda_i + \mu_t + \theta_{it}, \quad (7)$$

in which most variables have the same meanings as those in Equation (6), and φ_j is a regression coefficient. Changes in φ_j in different periods before and after the opening of an HSR line were investigated, and the results are shown in Figure 4.

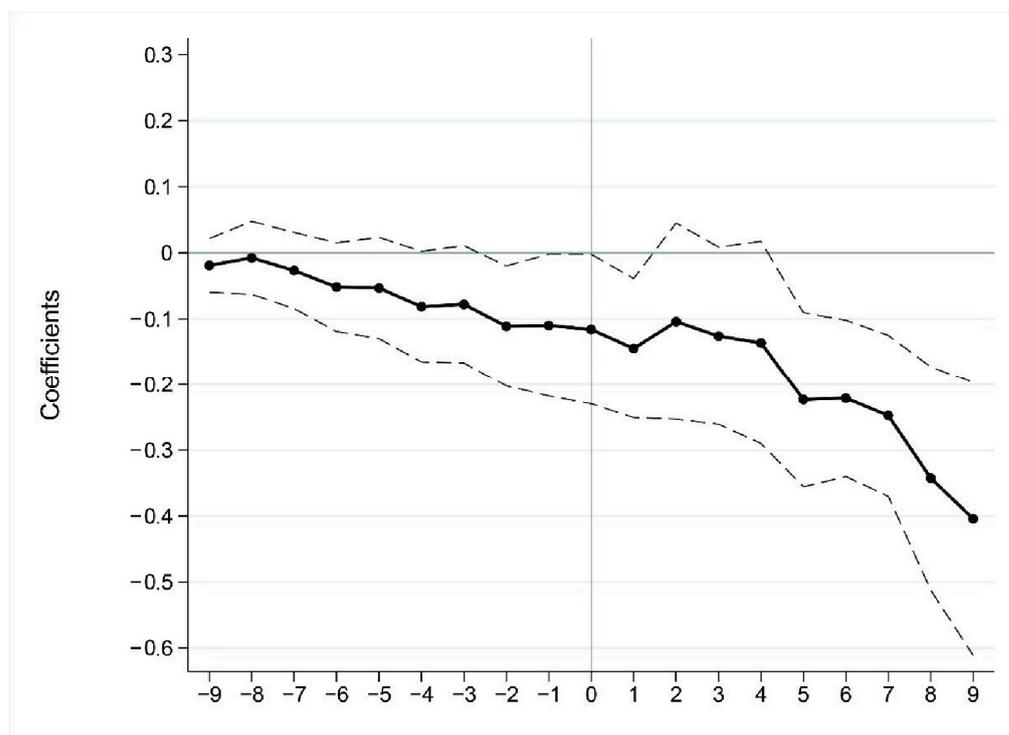


Figure 4. Dynamic effect graph showing regression coefficients φ_j before and after HSR line opening. Dashed lines indicate the 95% confidence interval.

It can be seen that, before the opening of an HSR line ($T = -9, T = -8, \dots, T = -1$), the value of φ_j fluctuated around 0, with the 95% confidence interval containing the 0 value. This indicates that the changes in the coefficient during this period are not large. It can be considered that before the opening of the HSR line, the fluctuations in carbon intensity are not obvious, and there is a parallel trend. After the opening of an HSR line ($T = 1, T = 2, \dots, T = 9$), especially after $T = 5$, the values of φ_j show a significant downward trend, and the 95% confidence interval no longer contains 0. Therefore, the sample data in this paper are consistent with the parallel trend hypothesis before the opening of an HSR line, and the DID estimation can be used.

The carbon intensities (CI) of 116 RBCs were examined by time varying DID regression. The results in Table 3 show that the variables of HSR line opening have a significant negative impact on carbon intensity; the HSR·open variable effectively reduces the carbon intensity of cities, and the carbon intensity of cities in which an HSR line opened was 0.054% lower than that of cities without an HSR line under the same control variables. Due to the possibility of endogenous problems in the model, there may have been biased estimation of the regression coefficients. Therefore, two-stage least-squares estimation

was applied by introducing an interaction item for the slope and time as the instrumental variable [46]. Under strong instrumental variable estimation, the HSR·open variable still played a significant role in reducing urban carbon intensity, and the coefficients of other variables also showed the same negative or positive effects.

Table 3. Baseline results of carbon intensity of RBCs in the full sample.

Variable	(1)	(2)	(3)	(4)	(5)
HSR·open	−0.135 *** (0.023)	−0.132 *** (0.023)	−0.058 ** (0.025)	−0.054 ** (0.025)	−0.067 ** (0.026)
In			−0.122 *** (0.017)	−0.126 *** (0.017)	−0.098 *** (0.017)
Op			0.217 *** (0.004)	0.351 *** (0.004)	0.285 (0.444)
Fi			0.356 *** (0.107)	0.345 ** (0.115)	0.186 (0.120)
Is			0.051 (0.127)	−0.031 (0.131)	−0.001 (0.149)
Constant	0.478 *** (0.047)	0.472 *** (0.009)	0.306 *** (0.082)	0.349 *** (0.076)	1.090 *** (0.237)
Observations	1856	1856	1856	1856	1856
City FE	No	Yes	No	Yes	Yes
Time FE	No	Yes	No	Yes	Yes
IV estimation	No	No	No	No	Yes
CDW. F statistic	—	—	—	—	7260.1
R ²	0.025	0.018	0.056	0.056	0.281

Notes: **, and *** denote statistical significance at the 5%, and 1%, levels, respectively, and figures in parentheses show the standard error.

4.3. Robustness Check

In the above regression results, there may still be some problems caused by sample selection, such as the non-randomness of urban samples in different periods due to their geographical location, the non-randomness caused by urban HSR line opening times being concentrated in a certain period, or the sample size having a significant impact on the results. To ensure the robustness of the regression coefficient results, this study used three methods to test for robustness. Firstly, a propensity score matching DID (PSM-DID) method was applied to estimate the propensity of the basic data after matching. Secondly, the opening time of urban HSR lines was delayed for two phases to be re-estimated. Thirdly, re-estimation was conducted after eliminating samples at random.

The PSM method [47,48] carries out one-to-one nearest matching between a treatment group and a control group according to the logit model. A total of 1685 samples were matched, and DID regression was carried out on the successfully matched samples. The results still show that the opening of an HSR line in an RBC has a significant impact on the decline of its carbon intensity. In the second and third methods, the conclusions were also found to be consistent. Therefore, it can be said that the opening of an HSR line in an RBC has a significant role in promoting the decline of its carbon intensity. The results from all three methods are shown in Table 4.

For a further robustness check, placebo tests were performed in order to ensure that the carbon intensity of RBCs would not be affected by random factors such as the variable HSR·open is one or zero. When control variables are fixed, we take the variable HSR·open in any one RBC as one randomized trial to estimate the coefficient of explanatory variable, and the variable HSR·open satisfies a 0–1 distribution. If the regression coefficients of the variable HSR·open of multiple randomized trials are concentrated around zero values,

it indicates that the carbon intensity of RBCs would not be affected by random factors such as the variable HSR-open, and the existing result is reliable, if not, the existing result is not reliable. Figure 5 shows the regression coefficients of the variable HSR-open of one thousand randomized trials concentrate around zero value, thus the coefficient of explanatory variable is reliable.

Table 4. Results of robustness tests of the baseline carbon intensity results.

Variable	(1) PSM-DID Model	(2) Two Lag Periods	(3) Random Sample Exclusion
HSR-open	−0.068 ** (0.025)	−0.027 (0.028)	−0.076 *** (0.025)
In	−0.109 (0.180)	−0.117 *** (0.017)	−0.096 *** (0.017)
Op	0.177 (0.477)	0.367 (0.463)	0.294 (0.444)
Fi	0.226 * (0.117)	0.488 *** (0.129)	0.178 *** (0.119)
Is	−0.061 (0.134)	−0.045 (0.144)	−0.005 (0.140)
Constant	0.419 *** (0.078)	0.272 *** (0.079)	0.392 *** (0.081)
Observations	1656	1856	1600
City FE	Yes	Yes	Yes
Time FE	Yes	Yes	Yes
R ²	0.042	0.055	0.045

Notes: *, **, and *** denote statistical significance at the 10%, 5%, and 1%, levels, respectively, and figures in parentheses show the standard error.

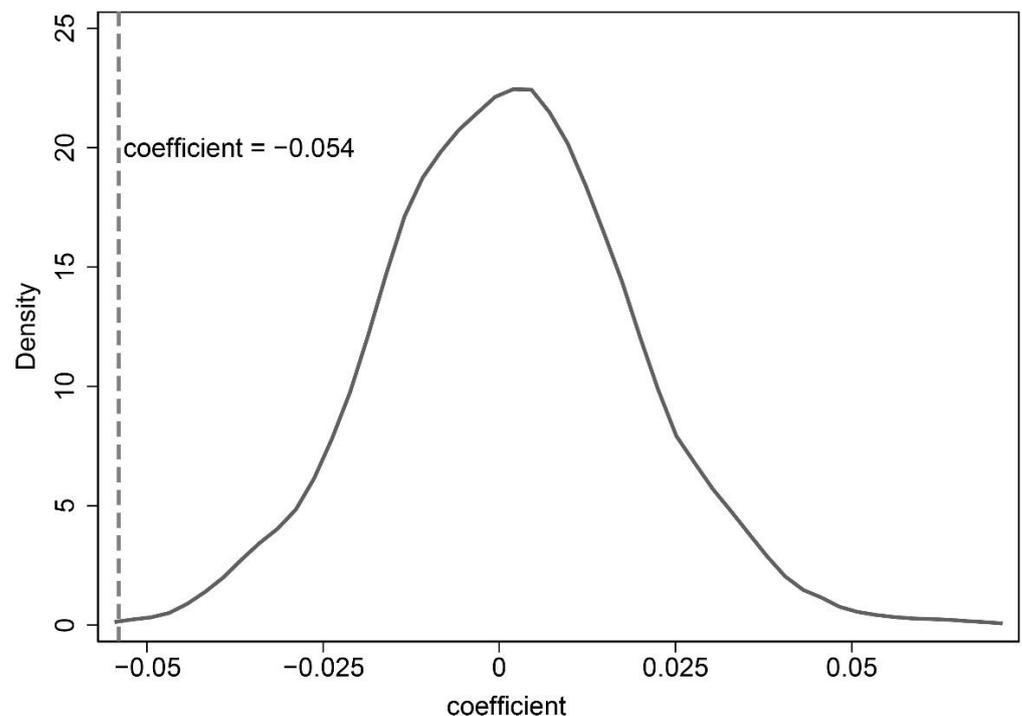


Figure 5. Regression coefficients of explanatory variables under randomized trials.

4.4. Heterogeneous Effects for Different Types of RBC

Similar regressions were conducted to examine the effect of HSR line opening on the carbon intensities of RBCs in the four different development stages. Obvious negative impacts on carbon intensity were found in cities in all four stages (Table 5). The opening of an HSR line will help to accelerate the inflow of innovation factors and inject vitality into the economy [49], thus promoting the progress and diffusion of clean technology and effectively reducing carbon intensity. Opening an HSR line in a recessive RBC was found to have the greatest impact on the decline of carbon intensity, reaching a relative change of -0.709 units, and this change was significant at the 1% level. Recessive RBCs will have a greater response to new technologies due to the exhaustion of their resources and their lagging economic development. The mature RBCs had relative change in carbon intensity of -0.078 units, and the change were significant at the 1% level. Therefore, for RBCs, it can be said that the opening of an HSR line is significantly favorable for decreasing carbon intensity at the mature and recessive stages of resource-industry development.

Table 5. Regression results of carbon intensity for RBCs at different development stages.

Variable	(1) Growth Type	(2) Mature Type	(3) Recessive Type	(4) Regenerative Type
HSR·open	−0.029 (0.035)	−0.078 *** (0.017)	−0.709 *** (0.110)	−0.072 (0.085)
In	−0.631 *** (0.162)	−0.073 *** (0.011)	−0.201 * (0.115)	−0.161 *** (0.029)
Op	−0.040 (0.113)	0.050 (0.045)	0.655 ** (0.331)	0.132 (0.115)
Fi	0.180 (0.163)	0.296 ** (0.087)	0.716 (0.477)	0.066 (0.211)
Is	−0.327 * (0.196)	−0.118 (0.094)	−0.339 (0.533)	0.055 (0.358)
Constant	0.513 *** (0.106)	0.346 *** (0.053)	0.735 ** (0.311)	0.386 ** (0.192)
Observations	240	1008	368	240
City FE	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes
R^2	0.106	0.107	0.185	0.200

Notes: *, **, and *** denote statistical significance at the 10%, 5%, and 1%, levels, respectively, and figures in parentheses show the standard error.

As noted earlier, the RBCs can also be divided according to their types of resources, specifically, forestry, oil and gas, metal mining, non-metallic-mineral mining, and coal mining. The opening of HSR lines in these five kinds of cities was also analyzed with respect to carbon intensity. It was found that the opening of an HSR line in three kinds of different RBC had a significant negative impact on carbon intensity (Table 6), reaching a significance level of 1%. Among these categories, the opening of an HSR line in coal RBCs had the greatest impact on the decline of their carbon intensity. Coal combustion is the main source of carbon emissions in China, and the carbon intensity of coal RBCs is therefore generally higher than that of other types of RBC. The carbon intensity reduction effect of HSR line opening in coal RBCs is significantly higher than that of other two types of city, reaching a relative change of -0.257 units, with significance at the 1% level. The effects of the HSR line opening on the carbon intensities of oil–gas and metal-mining RBCs were also significant, with relative changes of -0.188 and -0.124 units, respectively, significant at the 1% level.

Table 6. Regression results of carbon intensity for RBCs with different industries.

Variable	(1) Forestry Type	(2) Oil-Gas Type	(3) Metallic Type	(4) Non-Metallic-Mineral Type	(5) Coal Type
HSR·open	−0.024 (0.044)	−0.188 *** (0.040)	−0.124 *** (0.018)	−0.005 (0.046)	−0.257 *** (0.043)
In	−0.745 *** (0.126)	−0.318 *** (0.032)	−0.134 *** (0.010)	−0.204 *** (0.045)	−0.050 (0.030)
Op	0.104 (0.066)	−0.142 (0.091)	0.073 * (0.044)	0.215 ** (0.106)	−0.023 (0.028)
Fi	0.146 (0.304)	0.280 * (0.158)	0.195 ** (0.078)	0.618 ** (0.233)	0.107 (0.203)
Is	−0.812 ** (0.268)	−0.885 *** (0.205)	0.138 (0.107)	0.403 (0.302)	−0.137 (0.229)
Constant	0.646 *** (0.079)	0.875 *** (0.142)	0.279 *** (0.062)	−0.165 (0.163)	0.647 *** (0.120)
Observations	96	112	480	208	960
City FE	Yes	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes	Yes
R ²	0.362	0.609	0.413	0.164	0.053

Notes: *, **, and *** denote statistical significance at the 10%, 5%, and 1%, levels, respectively, and figures in parentheses show the standard error.

In addition, we are aware that the urban population size of RBCs also has different impacts. We classify the RBCs into three types according to their urban population, which are small cities with less than 500 thousand urban population, medium cities with less than 1 million and more than 500 thousand urban population, and big cities with over 1 million urban population. We then study the impact of HSR on carbon intensity of the three types of RBCs and find the difference among them (Table 7). In detail, the opening of HSR in medium-sized RBCs has the greatest impact on the decline of their carbon intensity, which is significant at 5%. However, the HSR has no significant impact on carbon intensity reduction of the other two types of RBCs.

Table 7. Regression results of carbon intensity for RBCs with different populations size.

Variable	(1) Small City	(2) Medium City	(3) Big City
HSR·open	0.0493 (0.035)	−0.127 ** (0.051)	−0.040 (0.035)
In	−0.321 *** (0.038)	−0.059 ** (0.025)	−0.217 *** (0.035)
Op	0.118 (0.082)	−0.028 (0.123)	0.397 *** (0.152)
Fi	0.707 *** (0.153)	−0.023 (0.217)	0.203 (0.209)
Is	−0.478 *** (0.160)	0.463 (0.287)	0.196 (0.243)
Constant	0.437 *** (0.086)	0.316 * (0.175)	0.226 (0.147)
Observations	928	624	304
City FE	Yes	Yes	Yes
Time FE	Yes	Yes	Yes
R ²	0.709	0.736	0.732

Notes: *, **, and *** denote statistical significance at the 10%, 5%, and 1%, levels, respectively, and figures in parentheses show the standard error.

4.5. Mediating Factors

The opening of HSR lines in RBCs strengthens their connections with the outside world and increases the inflow of production factors such as human resources and capital. The

inflow of human resources may reduce carbon intensity by improving the innovation level of RBCs with their talents. The inflow of capital may reduce carbon intensity by expanding the openness of RBCs to foreign capital investment and bringing in advanced production technology. The inflow of capital may also reduce carbon intensity by developing service industries and changing the industrial structure of RBCs to create a higher proportion of tertiary industries. In this way, the opening of an HSR line may reduce the carbon intensity of RBCs through direct mediating effects of migration and the indirect mediating effects of the innovation level, openness level, and industrial structure of RBCs.

In investigating the mediating effects of HSR line opening on carbon intensity in RBCs [50], it is helpful to further understand the mechanisms involved. The innovation level, openness level, financial self-sufficiency and industrial structure of the control variables RBCs in Table 2 are still introduced as control variables X_{jit} and migration in Table 2 is introduced as potential mediating variable M_{it} , and the following are constructed to test their mediating effects:

$$CI_{it} = s_0 + s_1 \cdot HSR_i \cdot open_{it} + h_j \sum X_{jit} + \lambda_i + \mu_t + \theta_{it} \quad (8)$$

$$M_{it} = s_0^M + s_1^M \cdot HSR_i \cdot open_{it} + h_j^M \sum X_{jit} + \lambda_i + \mu_t + \theta_{it} \quad (9)$$

$$CI_{it} = s_0^{CI} + s_1^{CI} \cdot HSR_i \cdot open_{it} + s_2^{CI} \cdot M_{it} + h_j^{CI} \sum X_{jit} + \lambda_i + \mu_t + \theta_{it} \quad (10)$$

where $s_0, s_1, h_j, s_0^M, s_1^M, h_j^M, s_0^{CI}, s_1^{CI}, s_2^{CI}$, and h_j^{CI} are the corresponding regression coefficients, X_{jit} represents the j control variables in Table 2, and the other variables have the same meanings as in Equation (6).

According to the mediating effect principle, s_1, s_1^M , and s_2^{CI} all pass the significance test, and if the absolute value of the coefficient s_1^{CI} is smaller than s_1 or its significance level is lower, M_{it} is a mediating variable. Table 8 shows the results of estimation of the mediating effects based on time varying DID regression. It can be seen that the migration of RBCs has a significant mediating effect. From the impact of an HSR line on carbon intensity in China's RBCs, when $M_{it} = \text{Migration}$, the coefficient HSR-open in Equation (9) is 0.565, and this is significant at the 1% level. This shows that the opening of an HSR line increases the migration of population and directly improved the urban innovation levels. The coefficient M in Equation (10) is -0.0006 , significant at the 5%, level while HSR-open is -0.053 , significant at the 5% level. The coefficient HSR-open in Equation (8) is -0.054 , significant at the 5% level. The absolute value of this coefficient is smaller, and its significance level is unchanged, which indicates that an HSR line accelerates the migration of RBCs, and this is the most effective intermediate way to enhance the impact of HSR on the reduction of carbon intensity.

Table 8. Results of mediating effect tests.

Variable	$M_{it} = \text{Migration}$		
	Equation (8)	Equation (9)	Equation (10)
HSR-open	-0.054^{**} (0.025)	0.565^{***} (0.021)	-0.053^{**} (0.024)
M			-0.0006^{**} (0.0002)
Observations	1856	1856	1856
Control	Yes	Yes	Yes
City FE	Yes	Yes	Yes
Time FE	Yes	Yes	Yes
R^2	0.056	0.103	0.117

Notes: **, and *** denote statistical significance at the 5%, and 1%, levels, respectively, and figures in parentheses show the standard error.

5. Discussions

This paper focuses on the causal effect of the opening of HSR line on the reduction of carbon intensity in RBCs. In general, we find that the impact on carbon intensity reduction is significantly positive. Previous research mostly focused on the impact of HSR on urban carbon emissions, which have demonstrated that HSR reduce urban CO₂ in China [51] and in Japan [2]. However, scholars also found that although HSR reduce GHG emissions in Spain, the construction of HSR brings more GHG emissions [52]. Our paper resonates with such research in the aspect of carbon emission reduction. However, it is distinct from them with its main focus on China's RBCs. Carbon intensity of RBCs are relatively high [16]. Our results show evidence that HSR significantly improve the carbon efficiency in RBCs, especially in energy resource-based cities such as coal-based cities. These results advance current research on the environmental impact of transportation.

However, this paper may have two limitations. First, the HSR lines differ in size and length across the RBCs, which may have different impacts on carbon intensity of RBCs; second, the mechanism of the impact of HSR on reducing carbon intensity is much more complicated than what we can fully elaborate and test in this paper. These limitations should be improved in the future.

6. Conclusions and Policy Implications

Since the end of the 20th century, as a convenient, comfortable, and safe long-distance mode of transport, HSR lines have been built in many countries [53]. The existing literature has mostly examined the economic and environmental impacts of the opening of HSR lines on cities, but little attention has been paid to RBCs. This study used a time varying DID model to study the impact of an HSR line on the carbon intensity of RBCs in China, analyzing its mediating factors. The results show the following. (1) Looking at the difference before and after the opening of an HSR line in an RBC, it can be seen that opening an HSR line can significantly reduce the carbon intensity of an RBC. In the process of the analysis, the problem of selection bias was examined and robustness tests were applied, and the conclusions remained unchanged. (2) Among RBCs in mature and recessive development stages, the opening of an HSR line was found to have a significant effect on reducing carbon intensity. The carbon intensity reduction effect of HSR line is stronger in recessive RBCs than in mature RBCs. The results also show that the opening of an HSR line has a significant effect on reducing the carbon intensity of RBCs in three industry categories. The size of this effect decreased in the order: coal > oil-gas > metals mining RBCs. (3) Mediating effects tests using multi-phase DID regression found that the migration is an effective mediating factor for reducing the carbon intensity of RBCs, and through migration improving the innovation level of an RBC is an effective mediating way to reduce its carbon intensity with an HSR line.

The above conclusions lead to three relevant policy implications, as follows. (1) Reducing the carbon intensity of RBCs will help to achieve the national goal of reducing China's carbon intensity by 65% by 2030. At present, only 55.2% of RBCs are connected by HSR lines. In the follow-up implementation of China's medium- and long-term HSR planning, more HSR stations should be opened in RBCs, and this will help to strengthen the connections between RBCs and other regions, improve the inflow of high-quality production factors, and break the inherent development-path dependence of RBCs. (2) HSR construction is a long-term project with high investment. In HSR planning and construction, attention should be paid to the different characteristics of different types of RBCs, and priority should be given to the opening of HSR lines in coal-based RBCs and medium RBCs in concern of the goal of reducing carbon intensity. This will help to reduce the carbon intensity of China's RBCs to the greatest possible extent. (3) As an effective mediating factor for reducing the carbon intensity of RBCs with HSR lines, removing population flow barrier would promote talents flow, eliminating mechanisms and systems that hinder the inflow of innovation factors such as talents and technology. Since the opening of HSR lines also presents the risk of the loss of local high-quality production factors, it is yet

more important to strengthen the measures and efforts applied to encourage innovative factors to flow into RBCs. This will make the intermediary path of HSR lines in RBCs more effective for reducing carbon intensity and help China to achieve its carbon peak and carbon-neutrality goals as soon as possible.

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