Development of High-Speed Rail, Agglomeration of Productive Service Industry, and Industrial Pollution Emission: Analysis Based on Three Major Urban Agglomerations in the Yangtze River Economic Belt

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Research Article

Keywords: high-speed railway, pollution emission, urban agglomeration, producer service accumulation, Yangtze River Economic Belt

Posted Date: April 28th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1512578/v1

Abstract

From the perspective of urban agglomeration, this paper studies the spatial correlation between pollution emission and industrial agglomeration and explores the impact of high-speed railway (HSR) development on urban industrial pollution emission and its internal mechanism. Based on the panel data of cities in three major urban agglomerations of the Yangtze River from 2007 to 2019, the entropy method is used to calculate the urban pollution reduction index, and the economic and environmental effects of HSR are investigated using combined double difference and spatial econometric techniques. The results show that: (1) HSR is helpful to alleviate pollution emissions; (2) HSR promotes the aggregation of local and neighboring producer services; (3) The accumulation of producer services plays an important intermediary role in the emission reduction effect of HSR and has positive spillover effects; (4) HSR has positive effects on the reduction of urban pollution in the Yangtze River Delta and Chengdu-Chongqing urban agglomeration, but it has negative effects on the middle reaches of the Yangtze River. The intermediary role of producer service agglomeration is more evident in the middle reaches of the Yangtze River and Yangtze River Delta.

1. Introduction

China's HSR operating mileage has reached 37,900 kilometers by the end of 2020. By 2035, China will build about 70,000 kilometers of HSR as a government plan, forming an "eight vertical and eight horizontal" HSR skeleton and a network connecting large and medium-sized cities and urban agglomerations. The impact of HSR on cities is profound and complex, and previous studies have focused on the economic effects of HSR, such as regional accessibility change, economic growth, spatial distribution, and development gap. The opening of HSR has produced time-space convergence effects. The optimization of accessibility further enhances the regional economic spillover effect with the gradual formation of the HSR network. Through the action of market economy, production factors have been reallocated in space, guiding the agglomeration trend of population and industry and reshaping the urban spatial structure (J. Wang & Ding, 2011). The profitability of factors determines the inevitable trend of its flow to the central area. The HSR line provides a more convenient channel for factor flow and promotes the generation of polarization effects. At the micro-level, HSR contributes to the transmission of "soft information", improves the efficiency of venture capital(Long, Zhao, Zhang, & Li, 2017), reduces the risk of share price collapse of locally listed companies(Zhao, Huang, & Liu, 2018), as well as enhances the operational efficiency of the capital market.

In order to achieve the purpose of "carbon peak" and "carbon neutralization", China's ecological environment construction will enter a new phase of focusing on carbon reduction and promoting the synergy of "pollution reduction" and "carbon reduction", in which the transportation industry plays a crucial role. The transportation industry contributes up to 25% of global carbon emissions, but it has not yet attracted enough attention. The comprehensive effect of industrial-technological progress increases carbon emissions (Ou & Wang, 2018). At the same time, carbon emission is also affected by differences in urbanization degree (Ou & Wang, 2021). This requires each city to formulate corresponding plans of scientific and implementable emission reduction according to its scale and level of economic development (Y. Wang & Ou, 2018). Specifically, the impact of HSR on the economy and environment is uneven, promoting the economic development of poor areas without improving local pollution emissions while reducing pollution emissions in rich areas without improving local economic development(Sun & Zhang, 2021). Optimal industrial allocation is crucial for high-speed rail to alleviate pollution emissions. High-speed railway can promote the inflow of productive service resources into central cities and accelerate the transfer of inefficient industries to surrounding cities. It is conducive to improving production efficiency and cultivating a scale economy to realize pollution mitigation(X. Fan, Xu, Nan, Li, & Cai, 2020).The accelerated flow of production factors in the HSR network has brought about the overflow of air and water pollution(Li & Guo, 2021). Overall, whether and how does HSR achieve emission reduction effect? The current view is that HSR can play a role in emission reduction by promoting factor structure optimization, industrial structure optimization, technological innovation, and opening-up, but with no consensus yet. Few studies have taken the spatial effect into account.

The Yangtze River Economic Belt is a major battlefield for green development and ecological priority in China, unblocking the double circulation aorta at home and abroad as well as guiding the high-quality economic development. The Yangtze River Economic Belt is of great significance to realize the expansion of economic growth space from along the line to inland along the river, promote the formation of a collaborative and interactive pattern between upstream, middle, and downstream, and narrow the development gap between the western, central and eastern regions. By November 2020, the HSR mileage in the Yangtze River had reached 40% of the total HSR scale in China. There is rare research on the comprehensive effect of HSR in the Yangtze River Economic Belt on the economy and environment in terms of urban agglomeration. The existing articles about the environmental effect of HSR have not considered the spatial correlation between pollution emission and producer service agglomeration. Here is the marginal contribution of this paper in the following aspects:

1. In terms of research content. Firstly, verify the spatial correlation between pollution emission and producer service agglomeration and explore the influence of HSR on pollution emission in local and adjacent areas. Secondly, investigate the intermediary role and heterogeneity of producer services that are more sensitive to HSR.
2. In terms of research objects. Select the three dominant urban agglomerations of the Yangtze River Economic Belt for analysis and subdivide the producer service industry to explore the degree of its action mechanism.
3. In terms of research methods. Firstly, integrate the idea of double difference into the spatial econometric model to explore the policy and spatial effects of the exogenous impact of HSR on pollution emission reduction. Secondly, use the intermediary effect model to test the degree of action mechanism, and summarize the spatial impact of HSR emission reduction effects and the regional and industrial heterogeneity characteristics of its internal mechanism.

2. Literature Review

2.1 High-speed railway and producer service agglomeration

Producer services are more dependent on human capital, knowledge and information flow than consumer services and public services and are more sensitive to traffic accessibility(Shao, Tian, & Yang, 2017). The opening of the HSR line strengthens the economic ties in the region, thus promoting the agglomeration of the service industry. The characteristics of its promoting effect include: in terms of action time, it increases with the increase of high-speed railway operation time (Qin & Yang, 2016), with a phased and lagging nature(Tang, Wu, Liu, & Li, 2021); In terms of object, HSR cities with agglomeration advantages at the beginning of the same urban agglomeration have a more significant positive impact(Cao, Hong, & Liang, 2019); In terms of action scope, the promotion effect disappears when the distance between the HSR station and the city center exceeds 30 km(Ma & Hao, 2020); In terms of internal mechanism, HSR can change the spatial agglomeration degree of producer services by improving location accessibility, reducing transaction costs, promoting the abundance of regional factors (Xuan, Lu, & Yu, 2019), facilitating factor integration and strengthening the spatial spillover effect (Qiao, Zhang, & Lei, 2019). The employment density of services in cities along the high-speed rail increased by 0.3%-0.4% for every 1% increase in the spatial effect of high-speed rail (Deng, Wang, & Cheng, 2017).

2.2 Producer service agglomeration and industrial pollution emission

The influence of producer service agglomeration (PSA) on pollution emission varies significantly in different regions, industries and cities. At present, most cities in China have not reached the “inflexion point” of the “inverted U” curve of the relationship between pollution emission and producer service agglomeration (Guo & Yuan, 2019). When reaching the inflexion point, the service industry can reflect its dual role in “steady growth” and “promoting emission reduction”. Large cities in eastern China have a higher level of industrialization, more substantial scale effect and environmental policy constraints. As a result, the “agglomeration inflexion point” of large cities in eastern China is significantly lower than that of small and medium-sized cities in central and western China (Chen, Sun, Lan, & Jiang, 2020). The high-end producer service agglomeration has an important inhibitory effect on pollution emissions in local and adjacent areas.

In contrast, the low-end producer service agglomeration has no significant influence (Lu & Wang, 2021). The inhibitory effect of diversified producer service agglomeration on pollution emissions is that the long-term impact is more significant than the short-term impact in both local and adjacent areas(Ren, He, Li, & Li, 2019). Based on the Marshall-Arrow-Romer externality, PSA exacerbates pollution; while reducing pollution in Jacobs and Porter externality(Ji, 2019). PSA can reduce industrial pollution emissions by promoting population agglomeration, optimizing economic structure, technology spillover, and helping to reverse the inhibitory effect of administrative monopoly on urban industrial pollution reduction(Liu & Gu, 2015).

2.3 High-speed railway and industrial pollution emission

Academia has not reached a consensus on the relationship between HSR and industrial pollution emission and its mechanism. Some of the materials for constructing a high-speed railway come from the production departments with high pollution and high energy consumption. The noise, vibration, electromagnetic radiation, sewage and solid waste generated in the operation process affect the ecological environment of cities along the line (Q. Wang & Lu, 2021). Meanwhile, the opening of HSR has induced a new demand for tourism and increased energy consumption to a certain extent (H. Zhang & Feng, 2019). HSR gradually shows the environmental benefits as a green and clean way of travel. It can not only replace other high energy consumption modes of transportation but also alleviate traffic congestion and effectively curb haze pollution. The larger the city size, the more pronounced the inhibition effect(J. Fan, Zhou, & Yu, 2021). Some scholars believe that HSR has the structural effect of promoting industrial agglomeration and upgrading as well as the technical effect of promoting innovation with knowledge spillover. These two effects are conducive to the due emission reduction effect of HSR. However, the scale effect of HSR that can promote economic development and energy consumption is challenging to measure the influence on the environment (H. Zhang & Feng, 2019). The accessibility change and network effect promoted by high-speed railway can improve the optimization of factor structure, helping the income and agglomeration of HSR as a positive role in pollution reduction (X. Fan & Xu, 2020). The HSR network also releases the contribution of service industry agglomeration to urban ecological efficiency and forms the green development effect of industrial structure(Luo, Tian, Yang, Li, & Wang, 2019). The innovation effect plays a vital role in promoting the efficiency of urban green development by high-speed rail (Ran, Zhang, & Yang, 2020). In addition, the opening expansion effect of high-speed rail can also reduce urban industrial pollution emissions to a certain extent (M. Zhang, Yu, & Sun, 2019).

On the one hand, HSR promotes pollution reduction by replacing other transportation modes and alleviating congestion. On the other hand, it improves the optimal allocation of factors and the upgrading of industrial structures by promoting accessibility and network relevance. The resources of knowledge-intensive producer services are greatly affected by HSR. With the help of its network, the spillover effect will further affect the level of urban industrial pollution emission (Fig. 1).

To sum up, the following hypotheses are put forward:

H1: High-speed railway improves the spatial agglomeration of producer services.

H2: The spatial agglomeration of producer services alleviates the emission of urban industrial pollutants.

H3: High-speed railway has the effect of pollution reduction, and the agglomeration of producer services is a meaningful way to realize its emission reduction effect.

3. Data And Methodology

3.1 Analytical sample

The research scope of this paper is the three major urban agglomerations of the Yangtze River, including the Chengdu-Chongqing urban agglomeration, the middle reaches of the Yangtze River urban agglomeration, and the Yangtze River Delta urban agglomeration.

Based on the data availability and research comparability, three county-level cities (Xiantao, Qianjiang and Tianmen) are excluded. The research objects include 70 prefecture-level cities and above. The statistical data come from China Demographic and Employment Statistical Yearbook, China Urban Statistical Yearbook, China Economic and Social Big Data Research Platform, EPS Data Service Platform and the State Railway Administration. The interpolation method is used to supplement the individual pollution emission data.

3.2 Calculation method

The core dependent variable is the pollution emission reduction index. To facilitate the follow-up mechanism analysis, the entropy method is used to treat the per capita industrial sulfur dioxide emission, per capita industrial smoke and dust emission, per capita industrial wastewater emission and capita industrial NOx emission as negative indicators for range standardization. The pollution emission reduction index is calculated after objective weighting to avoid the problem of information duplication between variables. The calculation steps of the panel data entropy method are as follows:

Range standardization:

$$Z_{tik} = \frac{z_{max} - z_{tik}}{z_{max} - z_{min}}$$

Normalization:

$$r_{tik} = Z_{tik} / \sum_{t=1}^{m} \sum_{i=1}^{n} Z_{tik}$$

Information entropy of each pollution index:

$$e_k = -\frac{1}{\ln(\mathrm{m} \cdot n)} \sum_{t=1}^{m} \sum_{i=1}^{n} r_{tik} \ln\left(r_{tik}\right)$$

Redundancy:

$$d_k = 1 - e_k$$

Weight of each indicator:

$$w_k = d_k / \sum_{k=1}^{h} d_k$$

Pollution reduction level:

$$PR_{ti} = r_{tik} \cdot w_k$$

Where z_{tik} refers to the index value of the city i in year t, r_{tik} is the proportion of various pollution emissions, $t \in \{1,2, \ldots, m\}$, $i \in \{1,2, \ldots, n\}$, $k \in \{1,2, \ldots, h\}$, $m = 13$, $n = 70$, $h = 4$. z_{max} and z_{min} represent the maximum and minimum values of different pollution indicators during all urban samples. After the above treatment, PR_{ti} is the pollution emission reduction level of the city i in year t. The larger the value, the more pronounced the pollution emission reduction effect of the city.

The independent variables include the development of high-speed rail (HSR) and the level of producer service agglomeration (PAL). At present, most studies on the high-speed rail set dummy variables based on whether to open high-speed rail, thus ignoring the dynamic change trend of high-speed rail service level. This paper measures the development level of HSR by using the number of HSR lines passing through the city. If an HSR line takes a city as the endpoint, it will open another section of the same line from the city next time. When the number of routes is calculated, the city is regarded as having opened two routes successively. During the process of calculating the producer service agglomeration level (PAL), to facilitate the number of employees in all relevant industries during the period of sampling, the scope of producer services is set as technical services, scientific research, finance, software, computer services, leasing and business services, information transmission, geological survey industries with high knowledge intensity, as well as transportation, storage and postal industries with low knowledge intensity. The existing indexes to identify the industrial agglomeration level include Herfindahl Hirschmann index, EG index, Moran index, spatial Gini coefficient and location entropy. The calculation of the Herfindahl Hirschmann index and EG index needs data accurate to the enterprise level. Based on the availability and integrity of data, this research calculates the global Moran index and location entropy to represent the spatial agglomeration level of producer services and selects the value of location entropy as the explanatory variable.

The calculation formula is as follows: $PAL_{iv} = \left(\frac{p_{iv}}{p_i}\right) / \left(\frac{P_v}{P}\right)$

PAL_{iv} represents the producer service agglomeration of the city i. The larger the PAL_{iv} value, the higher the agglomeration. PAL_{iv}>1 indicates that the sample is in a state of agglomeration, while PAL_{iv}<1 indicates that the sample city's PAL is lower than the regional average level. p_{iv} is the number of people engaged in the industry v of the city i, p_i is the total number of workers in the city i, P_v is the total number of people engaged in the industry v in the urban agglomeration, and P is the total number of workers in the urban agglomeration.

The control variables include the city's economic development level (PGDP), the opening-up level (FDI) calculated using the annual average exchange rate, the degree of government intervention (GI), urban scale (CS), technology investment (TI), environmental regulation (ER), information level (INL) and industrial structure (IND). Table 1shows the descriptive statistical analysis results of each variable.

Table 1
Summary statistics

Variable	Description	Obs	Mean	Std.Dev.	Min	Max
PR	pollution reduction level	910	0.850	0.148	0.127	1
HSR	HSR lines	910	0.884	1.278	0	8
PAL	PAS level	910	0.762	0.711	0.153	4.780
PGDP	per capita GDP	910	5.130	3.437	0.589	19.902
FDI	ratio of actually used foreign capital to GDP	910	0.026	0.034	0	0.889
GI	ratio of fiscal expenditure to GDP	910	0.159	0.058	0.058	0.675
CS	logarithm of total population at the end of the year	910	6.052	0.626	4.299	8.136
TI	ratio of science and technology expenditure to fiscal expenditure of the current year	910	0.023	0.019	0.002	0.163
ER	comprehensive utilization rate of industrial solid waste	910	0.873	0.168	0.05	1.432
INL	logarithm of Internet households	910	4.053	1.121	1.347	8.551
IND	ratio of tertiary industry to secondary industry	910	0.799	0.304	0.313	2.693

3.3 Model specification

3.3.1 Spatial correlation analysis

This study tests the spatial correlation using the global Moran's *I* index to demonstrate the rationality and necessity of using a spatial econometric model for empirical analysis. The Moran index is calculated using the row-normalized spatial weight matrix:

$$I = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^{n}(x_i - \bar{x})^2}$$

x_i is the observed value in the region i, x_j is the observed value in the region j, and w_{ij} is a factor in the row-normalized weight matrix w. The value range of *I* is [-1,1]. *I* > 0 represents positive autocorrelation, while *I* < 0 represents high-value and low-value aggregation. When *I* is close to 0, the observed value is distributed randomly in space without spatial correlation.

According to Tobler's First Law, the more geographically adjacent objects are, the more similar they are. Competition and cooperation among objects, imitation behaviour, overflow behaviour and unclear boundary definition are all reasons for spatial dependence. In this study, the economic-geographical space matrix is calculated by combining geographical and economic distances. The calculation formula is as follows:

$$W = W_{ij}^{d} \times W_{ij}^{e}$$

$$W_{ij}^{d} = \begin{cases} 1 / d_{ij}, \ i \neq j \\ 0, \ i = j \end{cases} \quad W_{ij}^{e} = \begin{cases} 1 / \left| \bar{e}_i - \bar{e}_j \right|, \ i \neq j \\ 0, \ i = j \end{cases}$$

The special variables are set as follow:

W_{ij}^{d}: The weight matrix of geographical distance

d_{ij}: The geographical distance calculated by longitude and latitude between city i and city j

W_{ij}^{e}: The weight matrix of economic distance in the period of sampling

$\bar{e}_i$: Per capita GDP in the sampling period of city i.

$\bar{e}_j$: Per capita GDP in the sampling period of city j.

W_{ij}^{d}, W_{ij}^{e} and W are all standardized. This paper uses MATLAB R2018b and Stata15.1 software for measurement and calculation. As shown in Table 2, the results indicate that the global Moran index is significant at the level of 1% during the sample period. From 2007 to 2019, PR and PAL in the prefecture-level cities of the three major city clusters have evident spatial agglomeration. Therefore, it is more scientific to choose a spatial econometric model for analysis.

Table 2
Moran index test results of PR and PAL

Year	2007	2008	2009	2010	2011	2012	2013
PR	0.505*** (7.152)	0.503*** (7.114)	0.543*** (7.733)	0.516*** (7.372)	0.415*** (5.905)	0.394*** (5.672)	0.417*** (5.926)
PAL	0.363*** (5.411)	0.415*** (6.372)	0.375*** (5.690)	0.362*** (5.513)	0.408***(5.995)	0.495*** (7.232)	0.476*** (7.080)
Year		2014	2015	2016	2017	2018	2019
PR		0.399*** (5.739)	0.373*** (5.346)	0.43*** (6.122)	0.466*** (6.643)	0.242*** (3.637)	0.457*** (6.516)
PAL		0.439*** (6.428)	0.412*** (5.992)	0.343*** (5.038)	0.387*** (5.705)	0.393*** (5.837)	0.398*** (5.912)

3.3.2 Model specification

The general expression for the spatial panel model is:

$$PR_{it} = \lambda WPR_{it} + \gamma X_{it} + \eta WX_{it} + \mu_{it} + \nu_{it} + \epsilon_{it}$$

$$\epsilon_{it} = \rho W\epsilon_{it} + \delta_{it}$$

In the model, PR_{it} represents the PR level of city i in year t, W refers to the spatial weight matrix, X_{it} refers to the set of control variables, μ_{it} and ν_{it} represent the time effect and individual effect, respectively, λ is the spatial autoregression coefficient, ρ is the spatial autocorrelation coefficient, γ and η respectively represent the parameter matrix to be estimated, and ϵ_{it} is the random disturbance term. When ρ=0 and η=0, it is a spatial autoregressive model (SAR) as follows:

$$PR_{it} = \lambda WPR_{it} + \gamma X_{it} + \mu_{it} + \nu_{it} + \epsilon_{it}$$

The SAR model considers the influence of adjacent areas on pollution emission, which is consistent with the results of spatial correlation analysis.

When λ=0 and η=0, the general expression for the spatial panel model turns into the spatial error model (SEM), considering the changes of local explanatory variables affected by the error term of adjacent areas via the spatial transmission mechanism, as well as the potential interference factors such as missing variables. The model is as follows:

$$PR_{it} = \gamma X_{it} + \mu_{it} + \nu_{it} + \epsilon_{it}$$

$$\epsilon_{it} = \rho W\epsilon_{it} + \delta_{it}$$

When ρ=0, the general expression for the spatial panel model turns into the spatial Dubin model (SDM), considering the influence of both local core variables and adjacent regional core variables on local explanatory variables. The model is as follows:

$$PR_{it} = \lambda WPR_{it} + \gamma X_{it} + \eta WX_{it} + \mu_{it} + \nu_{it} + \epsilon_{it}$$

The opening of HSR has an exogenous policy impact on the economy. This paper groups samples based on whether the city has high-speed rail or not. To estimate the net effect of SHR opening and spatial correlation between HSR and PR, the following basic SDM-DID equation is as follows:

$$PR_{it} = \lambda_0 WPR_{it} + \alpha_0 DID + \beta_0 WDID + \gamma_0 X_{it} + \eta_0 WX_{it} + \mu_{it} + \nu_{it} + \epsilon_{it}$$

(1)

In order to verify the intermediary role of PAL between HSR and PR, the stepwise regression models are as follows:

$$PAL_{it} = \lambda_1 WPAL_{it} + \alpha_1 DID + \beta_1 WDID + \gamma_1 X_{it} + \eta_1 WX_{it} + \mu_{it} + \nu_{it} + \epsilon_{it}$$

(2)

$$PR_{it} = \lambda_2 WPR_{it} + \theta PAL_{it} + \theta WPAL_{it} + \alpha_2 DID + \beta_2 WDID + \gamma_2 X_{it} + \eta_2 WX_{it} + \mu_{it} + \nu_{it} + \epsilon_{it}$$

(3)

DID is the interaction term between the policy dummy variable and the time dummy variable. This paper uses the number of HSR lines instead of the policy dummy variable to represent the HSR level of the city i in year t. When the sample city opens the high-speed rail, the policy dummy variable of the current year is 1; otherwise, it is 0. $\alpha_{0\tilde{2}}$ and $\beta_{0\tilde{2}}$ are the estimated coefficients of the double-difference term.

LM test and RLM test results show the SDM model is suitable for the existing data, and LR test and Wald test results indicate that it cannot degenerate into SAR or SEM (Table 3). The statistical value of the Hausman test is 73.70 and P = 0.000, indicating that the fixed effect is significantly better than the random effect.

Table 3
Model selection test results

test	statistic	P-value	test	statistic	P-value
LM-error	126.140	0.000	LR Test SAR	66.87	0.000
LM-lag	175.531	0.000	LR Test SEM	84.00	0.000
RLM-error	0.111	0.739	Wald Test SAR	24.33	0.004
RLM-lag	49.503	0.000	Wald Test SEM	26.02	0.001

The results of the counterfactual test and parallel trend test illustrate the feasibility of using the DID method in the model. In the multi-period DID model, $pre_{2\tilde{6}}$ represents the dummy variable before the HSR opening. PRE1 is removed from the estimation because it is the base period. The results (Table 4) show that the "pseudo-policy" variable has no significant effect on PAL and PR. As shown in Fig. 2, the change trends of PAL and PR in the control group (CG) and the treatment group (TG) during the sample period are almost the same, indicating that the data used in the analysis meet the assumption of using the DID model in terms of statistical significance and intuitive judgment.

Table 4
Parallel trend hypothesis test results

variable	PR	PAL
pre6	-0.014(-0.76)	0.033(-0.52)
pre5	0.008(-0.46)	-0.032(-0.71)
pre4	0.001(-0.07)	-0.041(-0.92)
pre3	-0.016(-1.41)	-0.062*(-1.71)
pre2	0(-0.03)	-0.035(-1.16)
Constant	-0.653(-1.49)	1.199(-0.63)
control variables	YES	YES
Year FE	YES	YES
City FE	YES	YES
R2	0.837	0.892
Observations	910	910

Notes: T-values in parentheses

4. Empirical Results

4.1 Baseline regression results

The VIF value of each variable is below 10, indicating no obvious multicollinearity among variables. Table 5 shows the main regression results of this paper, representing the regression results of model (1) controlling individual, time and two-way fixed effects, respectively. Spatial autoregression coefficients are significantly positive in all three fixed effects, suggesting that pollution emissions have an apparent positive spillover effect between cities. Such effect is more evident between cities closer to each other or has similar economic development levels, verifying the robustness of Moran's test results and the necessity of considering spatial effects in this paper. The results show that the DID coefficients of the interaction term are all significantly positive without taking into account control variables, preliminarily validating the hypothesis that HSRs help reduce pollution.

Basically, the regression coefficients of control variables are in line with the expected predictions. The increase of per capita GDP has aggravated pollution emissions, meaning the failure of the three urban agglomerations to fully achieve green economic development. The low value-added industries introduced by the opening-up policy have exacerbated pollution emissions to a certain extent. The emission reduction effect of HSRs is evident in larger-scale cities, which is attributed to more traffic congestion in those cities. Because of the greater demand for public transportation, HSRs play an essential substitute role for other modes of transportation.

The estimated result of the time-fixed effect model is significantly better than those of other fixed-effect models at the aspects of the goodness of fit and significance, thereby indicating that the following variable effect decomposition and heterogeneity were based on time fixed effect.

Table 5
Baseline regression result

	(1)		(2)		(3)	
	Entity fixed		Time fixed		Double fixed	
DID	0.009***	0.004	0.009***	0.010***	0.009***	0.003
	(2.89)	(1.11)	(2.59)	(2.87)	(2.86)	(0.93)
WDID	0.028***	0.020***	-0.052***	0.011	0.029***	0.019**
	(5.56)	(2.70)	(-6.97)	(1.07)	(3.98)	(2.21)
PGDP		-0.009**		-0.009**		-0.009**
		(-2.19)		(-2.07)		(-2.23)
FDI		0.013		-0.328***		0.025
		(0.2)		(-3.29)		(0.39)
GI		-0.054		0.095		-0.059
		(-0.77)		(1.18)		(-0.82)
CS		0.169***		0.043***		0.170***
		(5.14)		(3.79)		(5.16)
TI		0.227		0.037		0.245
		(1.03)		(0.14)		(1.10)
ER		0.003		0.063***		0.006
		(0.18)		(3.13)		(0.38)
LnINL		0.023***		-0.017*		0.016*
		(3.06)		(-1.79)		(1.87)
IND		0.005		0.087***		0.005
		(0.32)		(4.82)		(0.29)
Rho	0.375***	0.335***	0.642***	0.198***	0.346***	0.312***
	(8.15)	(7.00)	(19.71)	(3.83)	(7.28)	(6.38)
sigma2_e	0.004***	0.003***	0.012***	0.009***	0.003***	0.003***
	(21.02)	(21.07)	(20.61)	(21.23)	(21.05)	(21.10)
R^2	0.005	0.038	0.007	0.115	0.005	0.074

Notes: T-values in parentheses, *p < 0.1, **p < 0.05, ***p < 0.01.

	(1)		(2)		(3)	
Observations	910	910	910	910	910	910
Notes: T-values in parentheses, *p < 0.1, **p < 0.05, ***p < 0.01.						

4.2 Analysis of impact mechanism and effect decomposition

Based on theoretical analysis, models (2) and (3) were used to estimate the mediating effect of PAL and its degree of effect (Table 6). Without directly showing the full impact of explanatory variables on explained variables, the parameter estimates of variables in SDM cannot fully represent the marginal impact of HSRs. The estimated coefficients of explanatory variables include the direct effects of explanatory variables on explained variables and the feedback effect. Feedback effect means that the spillover effect of explanatory variables in the local area affects the adjacent area which feeds back this effect to the area through the spillover effect of explained variables. Columns (1) and (2) in Table 6 show that estimated coefficients and direct, indirect and spillover effect coefficients are all significantly positive, indicating that the development of HSRs plays a significant role in promoting PAL in both local and adjacent areas and simultaneously. The spatial agglomeration of service industries mitigates industrial pollution emissions in local and adjacent cities, validating Hypotheses 1 and 2.

As shown in column (3), regression coefficient and direct and total effects are all significantly positive, suggesting that HSRs are relatively effective in reducing pollution emissions. The indirect effect is insignificant, indicating that the impact of HSRs in other regions on the pollution emissions of a particular region is generally not apparent in the three urban agglomerations.

After the addition of the mediator variable (PAL) to Eq. (2), the estimated result in column (4) shows that PAL exerts a significant favorable influence on PR at the level of 1%. In addition, the regression coefficient, Z statistic value and significance of the interaction term are all reduced, indicating that PAL plays an intermediary role and verifying Hypothesis 3. Meanwhile, the direct and total effects of HSRs are no longer significant, indicating that the mediating role of producer service agglomeration is prominent. In other words, the emission reduction effect of HSRs is achieved mainly by promoting the agglomeration of producer services.

Table 6
Effect decomposition and mediating mechanism

	(1)	(2)	(3)	(4)
Variable	*PAL*	*PR*	*PR*	*PR*
DID	0.084***		0.010***	0.006*
	(4.74)		(2.87)	(1.67)
PAL		0.024***		0.023***
		(3.62)		(3.35)
WDID	0.327***		0.011	-0.002
	(6.42)		(1.07)	(-0.17)
WPAL		0.057***		0.053***
		(3.31)		(3.01)
Direct effect	0.105***	0.027***	0.011***	DID 0.006(1.63)
	(5.67)	(3.99)	(3.00)	PAL 0.025***(3.75)
Indirect effect	0.453***	0.071***	0.016	DID -0.002(-0.13)
	(6.32)	(3.55)	(1.29)	PAL 0.067***(3.18)
Total effect	0.557***	0.098***	0.028**	DID 0.005(0.35)
	(7.24)	(4.99)	(2.06)	PAL 0.092***(4.26)
Rho	0.259***	0.164***	0.198***	0.163***
	(4.97)	(3.14)	(3.83)	(3.12)
Sigma2_e	0.209***	0.009***	0.009***	0.009***
	(21.17)	(21.26)	(21.23)	(21.26)
Observation	910	910	910	910
R^2	0.193	0.036	0.115	0.041
Control variables	YES	YES	YES	YES

4.3 Robustness tests

To ensure the robustness of the estimation results, geographic, economic and population-geographic distance matrices were used to replace the economic-geographic distance matrix for robustness testing - The test results are shown in Tables 7, 8 and 9 shown. After the use of the three replacement matrices, the model estimation results show that the impact of HSRs and PAL on PR is significantly positive, verifying the robustness of the above regression results.

After replacement with geographic and population-geographic distance matrices, the results show that the spatial effect of PR has declined, indicating that PR is more affected by the similarity of the economic level, and also proving the rationality of choosing the above economic-geographic distance weight matrix.

Table 7
Robustness tests (geographic distance matrix)

Variables	***PAL***	***PR***	***PR***	***PR***	
DID	0.027(1.47)		0.010*(2.54)	0.009**(2.31)	
PAL		0.018**(2.50)		0.019***(2.60)	
Direct effect	0.020(1.00)	0.019**(2.50)	0.010*(2.47)	DID	0.009**(2.24)
				PAL	0.019***(2.66)
Indirect effect	0.218***(2.75)	0.080(1.22)	-0.051*(-1.73)	DID	-0.066**(-2.21)
				PAL	0.093(1.27)
Rho	-0.736***(-4.32)	0.079(0.58)	0.074(0.54)	0.069(0.50)	
Observations	910	910	910	910	
R^2	0.507	0.018	0.021	0.010	

Table 8
Robustness tests (economic distance matrix)

Variables	***PAL***	***PR***	***PR***	***PR***	
DID	0.092***(5.45)		0.015***(4.10)	0.012***(3.32)	
PAL		0.033***(4.76)		0.029*** (4.12)	
Direct effect	0.091***(5.24)	0.034***(4.69)	0.015*** (4.05)	DID	0.013***(3.23)
				PAL	0.032**(4.18)
Indirect effect	0.109**(2.37)	0.015(0.60)	0.010 (0.82)	DID	0.004(0.36)
				PAL	0.012(0.47)
Rho	-0.084(-1.35)	0.162***(2.71)	0.144** (2.37)	0.153** (2.53)	
Observations	910	910	910	910	
R^2	0.197	0.090	0.179	0.109	

Table 9
Robustness tests (population-geographic distance matrix)

Variables	***PAL***	***PR***	***PR***	***PR***	
DID	0.092***(5.49)		0.016**(4.43)	0.012***(3.20)	
PAL		0.036***(5.02)		0.033***(4.60)	
Direct effect	0.095***(5.50)	0.035***(4.78)	0.017***(4.38)	DID	0.012***(3.29)
				PAL	0.032**(4.55)
Indirect effect	0.144**(2.43)	0.049***(2.81)	-0.022*(-1.93)	DID	-0.034***(-3.04)
				PAL	0.055***(2.89)
Rho	0.077(1.37)	-0.091(-1.48)	-0.066(-1.07)	-0.076(-1.24)	
Observations	910	910	910	910	
R^2	0.239	0.075	0.192	0.071	

4.4 Heterogeneous effects

To eliminate the impact of differences between urban agglomerations on objective weighting, the samples were grouped by urban agglomerations, and then re-calculation was conducted respectively. The re-calculated PR and location entropy were used in equations to estimate the regional heterogeneity of HSR emission reduction and PAL mediation effects. The heterogeneous test results are presented in Table 10 below.

The pollution discharge of the Yangtze River Delta urban agglomeration has a positive spatial effect. That is, the pollution discharge level of a specific area will be affected by the pollution discharge of its adjacent areas. For every 1% emission reduction in the adjacent area, the pollution discharge in this area declines by 0.19%. A noticeable negative spatial effect exists on PR in the middle reaches of the Yangtze River urban agglomeration. Still, in the early development phase, the Chengdu-Chongqing urban agglomeration has not fully achieved joint development. The links between cities are not close enough.

The HSRs in the Yangtze River Delta and Chengdu-Chongqing urban agglomerations have produced significant emission reduction effects as the results are all significantly positive at the level of 1%. In contrast, the effect in middle reaches urban agglomerations is not apparent, exacerbating pollution emissions.

In the Yangtze River Delta urban agglomeration, the direct positive effect of HSRs is pronounced. In the meantime, a negative spillover effect on neighboring marginal cities indicates that the existence of the siphoning effect generated by HSRs aggravates pollution emissions. Overall, the negative spillover effect is greater than the positive effect of HSRs. However, the spillover effect of HSRs is not evident in middle reaches and Chengdu-Chongqing urban agglomerations. The results with the addition of mediating variables show no change in the significance of the DID estimate coefficients of the three urban agglomerations. However, the coefficient values of the Yangtze River Delta and middle reaches urban agglomerations have decreased, once again verifying Hypothesis 3, namely the critical mediating role of PAL. The DID estimation coefficient of the Chengdu-Chongqing urban agglomeration has become more extensive, indicating that the PAL of the Chengdu-Chongqing urban agglomeration has not yet achieved effect on PR during the sample period, where was before the “inflexion point” of the “inverted U-shaped” curve relationship between the two.

Table 10
Regional heterogeneous test results

	PR	the Yangtze River Delta		the middle reaches		Chengdu-Chongqing	
coefficients	*DID*	0.016**(2.27)	0.014** (2.08)	-0.017** (-2.52)	-0.015** (-2.28)	0.026*** (3.31)	0.028*** (3.62)
	PAL		0.039* (1.91)		-0.011 (-1.19)		0.011 (0.88)
Spillover Effect	*DID*	-0.056*** (-3.40)	-0.062*** (-3.78)	0.001 (0.05)	0.005 (0.22)	-0.004 (-0.24)	0.005 (0.26)
	PAL		0.085** (2.16)		-0.033 (-1.12)		0.203*** (3.61)
Direct Effect	*DID*	0.013* (1.87)	0.012* (1.73)	-0.017** (-2.35)	-0.015** (-2.20)	0.027*** (3.27)	0.028*** (3.55)
	PAL		0.042** (2.15)		-0.01 (-1.06)		0.004 (0.29)
Indirect Effect	*DID*	-0.064*** (-3.11)	-0.070*** (-3.72)	0.006 (0.33)	0.006 (0.37)	-0.006 (-0.32)	0.001 (0.06)
	PAL		0.108** (2.31)		-0.024 (-0.91)		0.194*** (3.54)
Total Effect	*DID*	-0.050** (-2.26)	-0.058*** (-2.75)	-0.011 (-0.67)	-0.009 (-0.55)	0.021 (1.10)	0.029 (1.55)
	PAL		0.149*** (3.27)		-0.034 (-1.26)		0.198*** (3.45)
Rho		0.191** (2.35)	0.154* (1.89)	-0.301*** (-3.57)	-0.294*** (-3.47)	-0.098 (0.356)	-0.097 (-0.92)
sigma2_e		0.009*** (12.94)	0.009*** (12.95)	0.011*** (13.34)	0.011*** (13.34)	0.003*** (10.32)	0.002*** (10.36)
Observations		338	338	364	364	208	208
R^2		0.142	0.036	0.01	0.016	0.549	0.142

The five main categories of the productive service industry were analyzed, and the regression results are shown in Table 11. The effect of HSRs has similar performance as above, which once again confirmed the robustness of the above regression results. The Yangtze River Delta region has formed an intensive HSR network. The economic activity between these cities has been dense, and the positive spillover effect is noticeable.

HSR systems have been developed in middle reaches urban cities, especially Wuhan which has turned into the largest transportation hub in the central region. However, the gap between central and marginal cities is more significant on account of the negative spillover effect. The Chengdu-Chongqing urban agglomeration has not informed the pronounced spatial effect of PAL. Surrounding cities have not benefited from the development of central cities. i.e., a negative spillover effect on financial industry agglomeration.

Labor flow is influenced sensitively by HSRs. Specifically, HSRs have promoted the agglomeration of information transmission, computer service and software industries in three urban regions. In addition, the scientific and technological research and technical services in the Yangtze River Delta region, the rental and business service industry in middle reach regions as well as the financial industry in the Chengdu-Chongqing region agglomerated are further under the impact of HSRs.

The intermediary effect of information transmission computer service and software industry agglomeration in the Yangtze River Delta region and the financial industry agglomeration in the Chengdu-Chongqing region play an important intermediary role in promoting pollution reduction.

Table 11

Industry heterogeneous test results

	Region	Yangtze River Delta		Middle reach		Chengdu-Chongqing	
industry	Observations	*PAL*	*PR*	*PAL*	*PR*	*PAL*	*PR*
Information Transmission Computer Services and Software Industry	*DID*	0.075**	0.017**	0.116***	-0.017**	0.194***	0.028***
		(2.24)	(2.47)	(4.05)	(-2.52)	(2.76)	(3.46)
	PAL		-0.019*		-0.011		-0.011
			(-1.66)		(-0.90)		(-1.45)
	Rho	-0.115	0.190**	-0.189**	-0.298***	-0.105	-0.092
		(-1.49)	(2.35)	(-2.14)	(-3.53)	(-0.95)	(-0.87)
	sigma2_e	0.212***	0.009***	0.207***	0.011***	0.198***	0.002***
		(12.95)	(12.94)	(13.44)	(13.34)	(10.30)	(10.35)
	Observations	338	338	364	364	208	208
	R^2	0.355	0.197	0.133	0.055	0.666	0.409
Financial industry	*DID*	-0.007	0.015**	0.113	-0.017***	0.070*	0.026***
		(-0.55)	(2.22)	(1.57)	(-2.62)	(1.76)	(3.39)
	PAL		0.056**		0.008*		0.026*
			(2.13)		(1.66)		(1.93)
	Rho	-0.170**	0.126	-0.323***	-0.298***	-0.206**	-0.117
		(-2.29)	(1.53)	(-3.22)	(-3.50)	(-2.08)	(-1.11)
	sigma2_e	0.036***	0.008***	1.304***	0.011***	0.063***	0.002***
		(12.96)	(12.96)	(13.23)	(13.33)	(10.30)	(10.41)
	Observations	338	338	364	364	208	208
	R^2	0.482	0.019	0.114	0.011	0.105	0.422
the scientific and technological research and technical services	*DID*	0.074**	0.015**	0.023	-0.016**	-0.04	0.032***
		(2.57)	(2.12)	(0.94)	(-2.43)	(-0.66)	(4.16)
	PAL		0.009		-0.053***		0.043***
			(0.66)		(-3.80)		(4.90)
	Rho	0.319***	0.181**	0.034	-0.301***	-0.16	-0.073
		(4.43)	(2.22)	(0.35)	(-3.59)	(-1.45)	(-0.69)

	Region	Yangtze River Delta		Middle reach		Chengdu-Chongqing	
	sigma2_e	0.160***	0.009***	0.146***	0.011***	0.150***	0.002***
		(12.92)	(12.94)	(13.58)	(13.34)	(10.42)	(10.27)
	Observations	338	338	364	364	208	208
	R^2	0.414	0.099	0.251	0.093	0.448	0.097
Transportation Warehousing and Postal Industry	*DID*	-0.001	0.015**	-0.021	-0.017***	-0.032	0.027***
		(-0.03)	(2.39)	(-0.47)	(-2.71)	(-0.68)	(3.37)
	PAL		0.098***		-0.036***		-0.009
			(6.33)		(-4.80)		(-0.76)
	Rho	0.462***	0.159**	-0.249***	-0.273***	-0.062	-0.096
		(6.73)	(1.98)	(-3.29)	(-3.25)	(-0.54)	(-0.90)
	sigma2_e	0.105***	0.008***	0.502***	0.010***	0.090***	0.002***
		(12.62)	(12.95)	(13.44)	(13.38)	(10.24)	(10.35)
	Observations	338	338	364	364	208	208
	R^2	0.377	0.07	0.262	0.026	0.656	0.359
Rental and business service industry	DID	-0.053**	0.015**	0.352***	-0.017**	-0.104*	0.025***
		(-2.05)	(2.17)	(4.29)	(-2.44)	(-1.89)	(3.17)
	PAL		-0.008		0.001		-0.008
			(-0.56)		(0.21)		(-0.78)
	Rho	0.182**	0.193**	-0.301***	-0.299***	-0.12	-0.083
		(2.37)	(2.39)	(-3.07)	(-3.55)	(-1.13)	(-0.78)
	sigma2_e	0.129***	0.008***	1.703***	0.011***	0.120***	0.002***
		(12.94)	(12.93)	(13.26)	(13.34)	(10.45)	(10.31)
	Observations	338	338	364	364	208	208
	R^2	0.411	0.029	0.139	0.012	0.677	0.357

5. Conclusions And Policy Implications

The entropy method was adopted to calculate the urban industrial pollution reduction level in the three major urban agglomerations of the Yangtze River economy from 2007 to 2019. On the basis of testing PR and PAL spatial relevance, and parallel change trend, and using the DID-SDM model, the relationship between HSRs and pollution emissions and the intermediary role of productive service industry agglomeration were explored, and finally regional and industry heterogeneous analyses were performed.

According to the model result, it was found in this paper that:

(a) With obvious spatial correlation, the aggregation of urban industrial pollution emissions and productive services is characterized by high value and high-value aggregation, low value and low-value spatial aggregation. The policy impact of HSRs can effectively alleviate urban pollution emissions. Besides, the expansion of urban scale, environmental regulation and industrial structure optimization are all beneficial to urban industrial pollution reduction.

(b) The improvement of local HSRs have an unobvious impact on the pollution emissions of neighboring cities but significantly promotes local and neighboring productive services. The agglomeration of productive services positively plays a significant intermediary effect during HSRs to generate an emission reduction effect.

(c) The regional heterogeneous results show that pollution emissions have a positive space effect in the Yangtze River Delta region, a negative effect in the middle reach region and no noticeable effect in the Chengdu-Chongqing region. The emission reduction effect of HSRs is more evident in the Yangtze River Delta and Chengdu-Chongqing regions. The intermediary role of productive service industry agglomeration is more evident in the Yangtze River Delta and middle reach regions.

(d) The industry heterogeneous test results show that the agglomeration levels of information transmission, computer service and software in three urban agglomerations are affected positively by the development of HSRs. The information transmission computer services and software industry in the Yangtze River Delta region and the financial industry agglomeration in the Chengdu-Chongqing region play an intermediary role in generating an HSR emission reduction effect.

Based on the findings, the following policy advice was given.

The first piece of advice is to build a long-term and effective cross-regional collaborative pollution control mechanism. The results show that pollution emissions between cities have an obvious spatial correlation. Under the influence of the spillover effect, separate pollution control cannot solve the pollution problem in the long term. Relative institutions are supposed to design policies based on regional integrity to improve policy efficiency.

The second one is to accelerate and reasonably plan the HSR network further to display the emission reduction effect of HSRs. The results show that HSRs can be of help to alleviate urban pollution emissions, and the orderly improvement of the HSR network can enhance the emission reduction effect. On the one hand, HSRs breaks the flow barriers of inter-regional economic elements, realizes the optimal spatial allocation of elements in a broader range, promotes the upgrading and transformation of economic structure, improves economic operation efficiency and alleviates pollution emissions. Nevertheless, it is necessary to reasonably plan the HSR line and reduce the uncoordinated regional development caused by siphoning effect. On the other hand, the Yangtze River economic belt is a leading demonstration area for China's economic growth and ecological civilization construction. The HSR coverage area and Yangtze River basin complement each other, which is convenient for middle reach and Chengdu-Chongqing regions to undertake the industrial transfer of the Yangtze River Delta, and conducive to realizing regional linkage and green economic development along the Yangtze River.

The third one is to continue to accelerate the development of producer services, especially knowledge-intensive and high value-added and high-end producer services, in the context of new normal economic development in China. HSRs and PAL are of vital importance to promote economic growth and mitigate pollution emissions. In the meanwhile, producer services play a significant intermediary role in the emission reduction effect of HSRs. At this stage, the pollution reduction effect of producer services in the three urban agglomerations still has excellent growth potential. Under the background of the development of new standard economy, it is necessary to pay full attention to the development and layout of producer services and accelerate the formation of a unique situation where the development of HSRs and producer services complement each other to provide new ideas and paths for promoting the realization of high-quality economic development.

Declarations

Data availability

The dataset used and analyzed during the current study are available from the corresponding author on reasonable request.

Ethics approval: Study did not use any data which need approval.

Authors Contributions: H.Z. designed the study, performed the research, analyzed data, and wrote the initial draft of the paper; O.G.L. refined the ideas, carrying out additional analyses and revisions; all authors contributed to the writing and revisions.

Funding: Not applicable.

Consent for publication: Not applicable.

Competing interests: The authors declare no competing interests.

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Figures

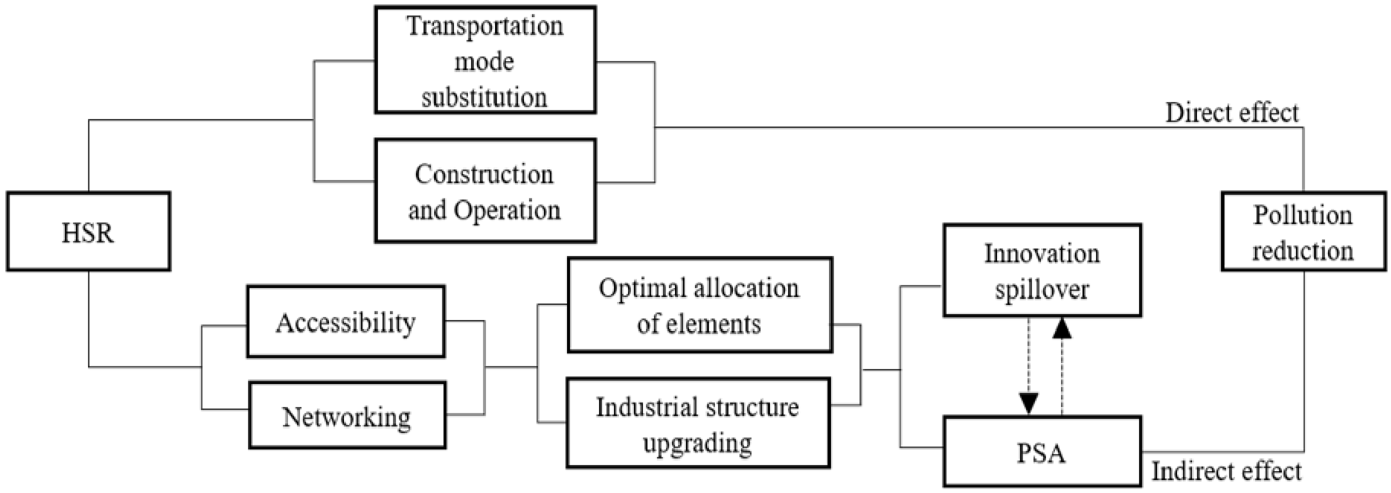

Figure 1

Action mechanism of high-speed rail development, producer service agglomeration and pollution reduction

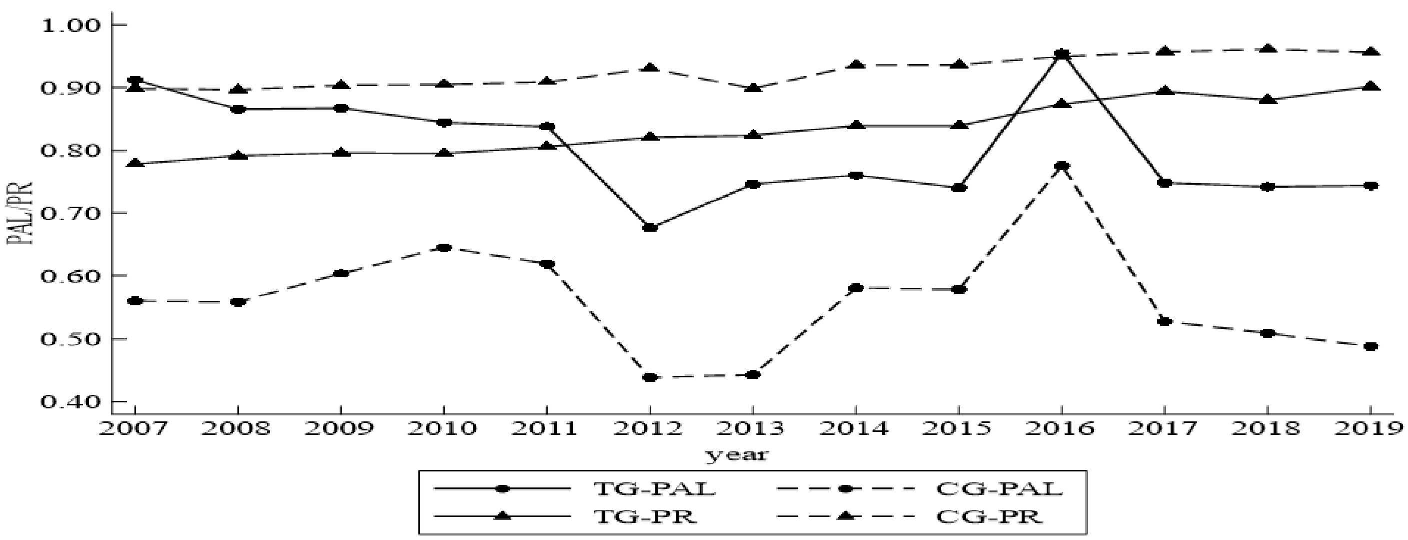

Figure 2

PAL and PR parallel trends