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Impacts of high-speed rail on urban smog pollution in China: A spatial difference-in-difference approach

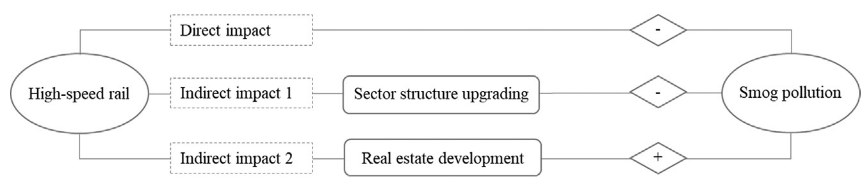
Jing Fang

School of Economics and Business Administration, Chongqing University, Chongqing 400044, China

HIGHLIGHTS

- A panel dataset is used comprising 284 Chinese cities from 2007 to 2016.
- The STIRPAT model and the environment Kuznets curve are introduced.
- Spatial difference-in-difference approach and causal mediation analysis are used.
- The impacts and two causal mediations of high-speed rail on smog are proved.
- The non-linear impacts of per capita GDP and population on smog are discussed.

GRAPHICAL ABSTRACT



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ABSTRACT

Smog pollution poses a severe threat to residents' health and economic development in China. High-speed rail (HSR) is a new and efficient infrastructure that is expected to provide economic and environmental benefits. Based on the STIRPAT model and the environment Kuznets curve (EKC) hypothesis, this study employs a spatial difference-in-difference approach using 284 prefecture-level cities' panel data from 2007 to 2016 to explore the impacts of HSR on urban smog pollution. The results demonstrate that urban smog pollution shows strong spatial correlations and that HSR can significantly reduce smog pollution. Causal mediation analysis is used to test two mechanisms related to HSR: sector structure upgrading, which can reduce smog pollution, and real estate market development, which tends to increase smog pollution. After controlling for the two opposite mechanisms, HSR is proven to have positive environmental benefits. Besides HSR, the impacts of per capita GDP and population on smog pollution are further discussed. The relationship between per capita GDP and urban smog pollution follows an N-shaped curve, and smog is proved to reduce to a certain extent as per capita GDP increases. The relationship between population and smog pollution shows a U-shaped curve, provided with a new interpretation relating to economies of scale. The findings have implications for policy-making, as they enrich the EKC hypothesis and provide evidence for the environmental benefits of HSR.

1. Introduction

Industrial development at the expense of the environment seems to be an inevitable problem in economic development, which is exactly what China is now facing. In particular, China's air pollution has received increasing attention (Wu et al., 2018). As early as 2004, smog pollution was publicly reported in Beijing for the first time (Zhang, 2004). Smog pollution shrouded the most developed urban agglomerations in China primarily (Hu et al., 2014) and has continued to spread across the country, increasing over time (Richter et al., 2005; Deng et al., 2008). Many studies have confirmed that air pollution like smog is a severe threat to residents' health (Franklin et al., 2007; Ito et al., 2011; Fann et al., 2012) and has caused high economic losses (Zhang and

E-mail address: fangjing@cqu.edu.cn.

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Crooks, 2015). Thus, controlling smog pollution is necessary to maintain long-term sustainable growth and improve public welfare (Li and Zhang, 2014).

High-speed rail (HSR) construction is one of the major changes in transportation technology in China. The "Four Vertical and Four Horizontal" high-speed rail networks have been constructed (NBS, 2019), with over 37,900 km of HSR being operating (NRA, 2021). And China is ambitiously planning and building the denser and faster "Eight Vertical and Eight Horizontal" HSR networks (see Fig. 1). The impact of HSR on economic development has attracted widespread attention (Pagliara et al., 2017; Xu et al., 2018). These studies have been instructive concerning the impact of HSR on economic development, but they have not widely discussed the comprehensive impact of HSR on urban economic development and smog pollution. By way of addressing this gap, this study uses panel data from 284 prefecture-level cities in China from 2007 to 2016 to research the impact of HSR on smog pollution. A spatial difference-in-difference (DID) approach is used, based on the classic STIRPAT model (York et al., 2003a, 2003b) and the Kuznets curve (EKC) hypothesis (Grossman and Krueger, 1995).

This paper finds that HSR is indeed beneficial for reducing urban smog pollution. Further, causal mediation tests support that HSR has both positive and negative heterogeneous effects as follows: (1) HSR can reduce urban smog pollution by promoting upgrades in the sector structure, and (2) HSR will stimulate the development of the real estate market, thus increasing smog pollution. After controlling for the two causal mediations, HSR shows a significant negative effect on smog pollution, which indicates that the suppression effect of HSR is greater than the aggravation effect. Besides HSR, this paper discusses the nonlinear impacts of per capita GDP and population increase on smog pollution. The relationship between per capita GDP and smog pollution follows an N-shaped curve, and urban smog pollution is proved to reduce to a certain extent as per capita GDP increases. The relationship between population and smog pollution shows a U-shaped curve, provided with a new interpretation relating to economies of scale. These findings can enrich theoretical research on the EKC hypothesis and contribute to policy-making aimed at China's development.

Compared with the existing literature, this study focuses on the synchronous impacts of HSR on smog pollution and economic activity promotion. It discusses the mechanism of HSR's impacts by introducing causal mediation analysis. One limitation is that once the causal mediation variable is proved to have significant effects on the dependent variable, the basic equation, without controlling the causal mediation variable, has omitted variable bias. However, this study compares the results with or without controlling the mediation variables and finds that the coefficients of independent variables, especially HSR, are robust. That is to say, this limitation is within the tolerances for this study, to a certain extent.

2. Literature review and hypotheses

Economic development is usually accompanied by environmental pollution problems, especially in developing economies. China's rapid

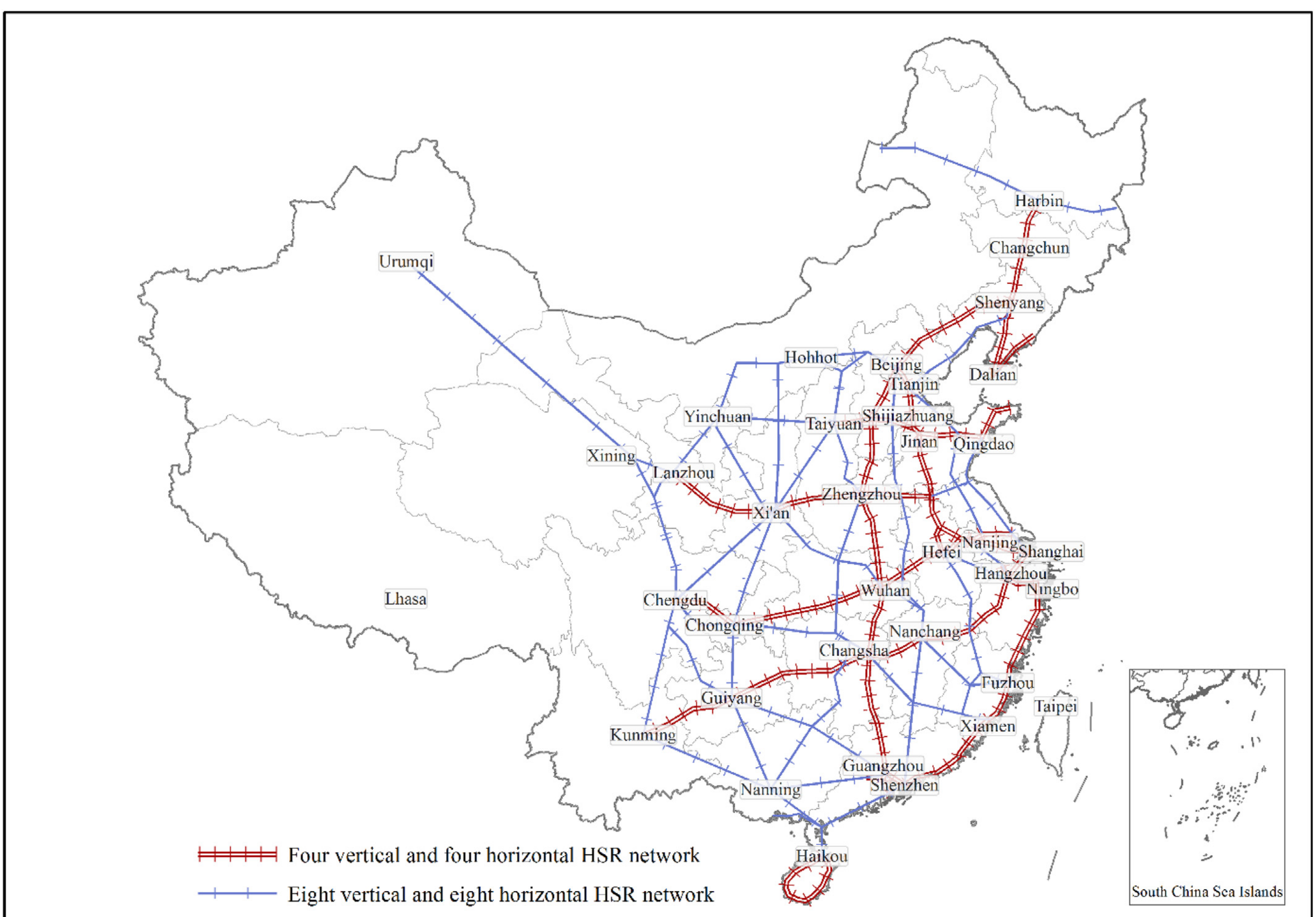

Fig. 1. The High-speed Rail Network of China to be completed by 2025. *GIS Sources: Medium and Long-term Railway Network Plan of China* (2016), National Geomatics Center of China (NGCC).

growth in the past 40 years has been, to some extent, at the expense of the environment (He et al., 2020). At present, China is in the critical period of crossing the middle-income trap, even as the traditional extensive development path has hit a bottleneck with slowing economic growth and severe smog pollution. Although pollutant emissions cannot be eliminated, they can be reduced by improving the energy structure (Wu et al., 2021). Improvements in transport infrastructure are often regarded as necessary for urban economic growth. Inter-city transportation is even more important in China because of its vast territory and uneven distribution of resources. However, traffic is also widely considered to be a main cause of air pollution (Colvile et al., 2001; Huang et al., 2016). The construction of roads and highways (O'Donoghue et al., 2007; Zhou and Lin, 2019), exhaust emissions and traffic congestion caused by the sharp increase of cars (Hou et al., 2018), and exhaust emissions from air transport (Cameron et al., 2017) have all worsened smog pollution. If electricity is increasingly used in the urban public transport sector, it will have a considerable impact on air pollutant emission reduction and smog pollution control (May, 2018; Xie et al., 2021).

China's HSR is a transportation infrastructure that uses electricity as its sole power source. Chester and Horvath (2012) agreed that HSR projects would provide significant environmental benefits compared with other existing transportation modes. Using HSR instead of other fossil fuel-powered transportation methods, such as air or road transportation, can reduce environmental pollution problems owing to less pollutant emission (Chiara et al., 2017; Chang et al., 2019).

Although HSR operates with electricity and, hence, with almost no emissions, the electricity is produced mainly by thermal power generation, which contributes the largest share of air pollutants in China (Xing et al., 2020). Yue et al. (2015) evaluated China's Beijing-Shanghai HSR over its whole life cycle and argued that the infrastructure construction of HSR and China's coal-based power generation structure made HSR's impact on smog pollution uncertain.

The foregoing different viewpoints discuss whether HSR will directly aggravate or alleviate smog pollution from the perspective of its power source. However, these studies did not examine the impacts that HSR has on economic development from multiple perspectives. The HSR network, aimed at being a nationwide inter-city corridor, has been linking more and more cities and profoundly changing China's development pattern (Qin, 2017; Ke et al., 2017). The expectation is that a highly developed urban transportation network will facilitate the travel of factor resources between cities so as to optimize the layout of sector structure, promote collaboration among urban agglomerations, and continuously expand the spillovers of knowledge and technology from developed regions (Yao et al., 2020).

The various economic production activities may have different effects on environmental pollution. For example, some economic activities can alleviate smog pollution, such as the upgrading of industrial structure. Chen et al. (2019) believe that the industrial structure dominated by heavy industry would exacerbate smog pollution, whereas increasing the proportion of the service sector in the industrial structure is conducive to reducing air pollution (Hao et al., 2020; Zhu et al., 2019). However, some economic development aspects will exacerbate air pollution problems, such as the development of the real estate market. Yao et al. (2019) pointed out that constructing more buildings causes more fossil fuel consumption, resulting in increasing environmental pressure and pollution problems and posing a health threat (Li et al., 2020).

HSR is considered to be related to these economic activities. First, the contribution of HSR to service sector development has been widely discussed (Shao et al., 2017). Focusing on the Yangtze River Delta, one of the most developed urban agglomerations in China, Wang et al. (2019) asserted that HSR could promote the optimization of the urban sector structure and increase the proportion of the tertiary industry. Likewise, Shao et al. (2017) studied this region and claimed that HSR projects had strengthened the agglomeration of productive service industries but that the impacts on the consumer service industry and public service industry were not significant. In addition, HSR may promote the industrial and service sectors to accommodate more employment (Lin, 2017) and facilitate residents' migration (Garmendia et al., 2008). As a result, however, HSR aggravates imbalances in the development of China (Faber, 2014; Diao et al., 2016; Diao, 2018; Dong, 2018; Qin, 2017; Zhang et al., 2020) and increases housing values (Chen and Haynes, 2015) and commercial land trade volumes (Wang et al., 2018) in those cities that have HSR.

In general, existing studies have discussed the impact of HSR on urban economic development from multiple perspectives, including the positive or negative effects on smog pollution. However, the aforementioned studies did not discuss the environmental benefits of HSR from the perspective of economic development, an issue that deserves more discussion. In view of all that has been mentioned so far, this paper proposes the following three hypotheses:

H1. HSR directly affects reduction in smog pollution.

H2. Sector structure upgrading, especially increases in the tertiary industry, is an indirect mechanism for HSR to ameliorate smog pollution.

H3. Real estate development, accompanied by increasing building energy consumption and emissions, is an indirect mechanism by which HSR exacerbates urban smog pollution.

To sum up, this study assumes that HSR projects have both direct and indirect impacts on urban smog pollution. The direct impact comes from power substitution; that is, HSR projects use a low-emission, all-electric power system, which is conducive to reducing urban smog pollution. The indirect impacts arise from the two mechanisms mentioned above: sector structure upgrading and real estate development. The former occurs by way of development in the tertiary industry, which aids smog pollution control. The latter manifests as increased dust and pollutant emissions from the building industry, thereby worsening smog pollution. Fig. 2 summarizes the three impacts.

3. Methodology and data

The STIRPAT model (York et al., 2003a, 2003b) and the environmental Kuznets curve (EKC) hypothesis (Grossman and Krueger, 1995) are the basic theoretical frameworks used to analyze the factors affecting environmental pollution (Shao et al., 2016). One of the main constituents of smog pollution is $PM_{2.5}$, a particulate matter with a diameter less than or equal to 2.5 μm, which is also the most harmful to human health. This study measures the degree of urban smog pollution with $PM_{2.5}$ concentrations. In terms of air pollution, more attention has recently been paid to the spatial correlations of urban smog (Hao and Liu, 2016; Miao et al., 2019). Therefore, this paper uses a spatial DID approach for synthetically analyzing city-level HSR projects, economic growth, and smog pollution.

3.1. The EKC hypothesis and the STIRPAT model with the impact of HSR

York et al. (2003a, 2003b) presented the STIRPAT model with a stochastic form on the basis of the IPAT framework established by Ehrlich and Holdren (1971). This model has been widely used to explore the causes of pollutant emissions (Wang et al., 2017). The basic STIRPAT model is as follows:

$$I_{it} = aP_{it}^{b}A_{it}^{c}T_{it}^{d}e \tag{1}$$

where I denotes environmental impact; P denotes population size; A denotes per capita wealth; T denotes technology; a denotes the model coefficient; b, c, and d are the exponents for the independent variables; and e denotes the error term. The greatest advantage of this model is that it allows the estimation of each coefficient as a parameter, as well as proper decomposition and improvement of each impact factor (Shao et al., 2011). For accuracy, I is measured by $PM_{2.5}$ concentration.

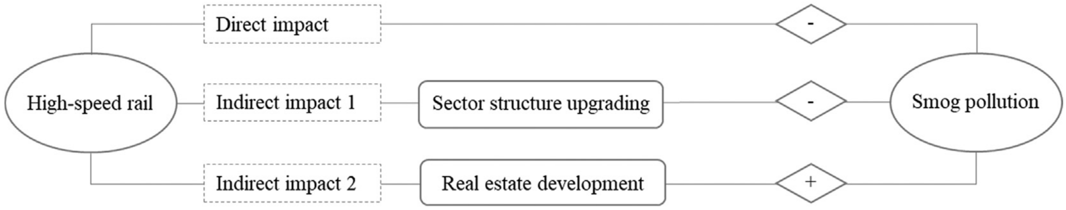

Fig. 2. The direct and indirect impacts of HSR on urban smog pollution.

In particular, per capita wealth (A) is usually calculated by GDP per capita, so the model is also suitable for analyzing the relationship between economic development and smog pollution.

Grossman and Krueger (1995) proposed the EKC hypothesis pointing out an inverted U-shaped relationship in which air pollution accompanied by economic growth first decreases and then increases. Some subsequent studies have further found that the two may also have other curved relationships, such as a U- or N-shape or even an inverted N-shape (Shao et al., 2016).

Regarding the impacts of population on the environment, Han et al. (2021) hypothesized that the nexus between the semi-urbanization of population and energy efficiency could be described as an inverted U-shaped curve. Huo et al. (2021) also asserted that the effects of urbanization on carbon emissions are nonlinear. Following these ideas, this study also proposes that the effects of population agglomeration on urban smog pollution may be nonlinear.

Based on the above analysis, the logarithm of the basic model is here combined with the EKC hypothesis to introduce the cubic term of economic development and the squared terms of population size into the equation. Furthermore, the difference-in-difference analysis (DID) is used to investigate the role of HSR as follows:

$$\begin{aligned} y_{it} = {} & \beta_0 + \beta_1 HSR_i \times After_t + \beta_2 \ln A_{it} + \beta_3 \ln A_{it}{}^2 + \beta_4 \ln A_{it}{}^3 + \beta_5 \ln P_{it} \\ & + \beta_6 \ln P_{it}{}^2 + \beta_7 \ln T_{it} + \beta_8 COV_{it} + \mu_i + \gamma_t + \varepsilon_{it} \end{aligned} \quad (2)$$

where y_{it} denotes $\ln(PM_{2.5})_{it}$. HSR_i is a dummy variable which equals 1 when city i is a city with HSR implementation. $After_t$ is a time dummy variable which equals 1 when year t is the year after HSR has been placed in service. Specifically, it is assumed that it will take some time for a city to reflect the impact of HSR. Therefore, $After_t$ equals 1 if HSR in city i has operated in the first half of the year; otherwise,$After_t = 0$ and $After_{t+1} = 1$. $HSR_i \times After_t$ is the DID term, which equals 1 only when city i has had HSR in service during year t; otherwise, it equals 0. A_{it} denotes GDP per capita, and $A_{it}{}^2$ and $A_{it}{}^3$ respectively denote the square and cubic terms of A_{it}. P_{it} denotes population, and $P_{it}{}^2$ denotes the square of P_{it}. T_{it} denotes technology and is measured by the ratio of scientific and technical industry employment to total employment. μ_i and γ_t, respectively, denote city and year-specific effects, and ε_{it} controls random errors. β_0 is a constant term. β_1 to β_8 are regression coefficients, respectively representing the impact of each independent variable on the dependent variable.

COV_{it} denotes some time-variant covariates that are generally thought to affect smog pollution. For general considerations, this study mainly controls foreign direct investment (*FDI*) and other passenger transport (*OPT*).

FDI is widely regarded as one of the socio-economic factors that affect air pollution (Cole et al., 2011; Hille et al., 2019). Given that discussions about the pollution haven and pollution halo hypotheses have not reached a unified conclusion (Liu et al., 2018; Xu et al., 2021), it is valuable to keep studying the spatial correlation of FDI and its impact on air pollution, especially smog pollution.

Traffic is widely considered to be one of the main causes of air pollution (Cameron et al., 2017; Colvile et al., 2001; Huang et al., 2016; O'Donoghue et al., 2007; Zhou and Lin, 2019). China's HSR is dedicated to passenger transportation (Yao et al., 2020). This paper controls the ratio of passenger volume to population size (*OPT*) of other inter-city vehicles—that is, air, road, and water transportation—to measure the impacts of other transportation modes on smog pollution. In this way, the net effects of HSR can be better identified.

3.2. The spatial DID analysis

Based on a general regression analysis, the spatial DID analysis further considers the spatial geopolitical relations measured by the spatial weighting matrix, considering that smog pollution is often spread to the surrounding areas by atmospheric circulation. Therefore, this paper introduces the most commonly used spatial contiguity weighting matrix $\mathbf{W}$. Each element w_{ij} of $\mathbf{W}$ represents the contiguity between cities. If city i and j share common boundaries and $i \neq j$, $w_{ij} = 1$; otherwise, $w_{ij} = 0$. In addition to neighboring relations, inverse distances can be used to construct w_{ij} (this will be further discussed in robustness checks).

Spatial correlation is the premise of spatial econometrics analysis. Here, Moran's I index (Moran, 1950) is used to test this as follows:

$$Moran = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(y_i - \bar{y})\left(y_j - \bar{y}\right)}{S^2 \sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}} \quad (3)$$

where *Moran* denotes Moran's I index. y_{it} denotes $\ln(PM_{2.5})_{it}$, and $S^2 = \sum_{i=1}^{n}(y_i - \bar{y})^2/n$. w_{ij} denotes the element of spatial contiguity weighting matrix $\mathbf{W}$.

The general spatial DID regression model is as follows:

$$\begin{cases} y_{it} = \rho \mathbf{WY} + \mathbf{WX}\boldsymbol{\delta} + \beta_1 HSR_i \times After_t + \beta_2 \ \ln A_{it} + \beta_3 \ \ln A_{it}{}^2 + \beta_4 \ \ln A_{it}{}^3 \\ \quad + \beta_5 \ \ln P_{it} + \beta_6 \ \ln P_{it}{}^2 + \beta_7 \ \ln T_{it} + \beta_8 COV_{it} + \mu_i + \gamma_t + \varepsilon_{it} \\ \quad \varepsilon_{it} = \lambda \mathbf{W}\boldsymbol{\varepsilon} + v_{it} \end{cases} \quad (4)$$

where $\mathbf{WY}$ and $\mathbf{WX}$ denote the respective spatial lags of the dependent and independent variables—that is, the average value of the neighbors. ρ is the spatial autoregression coefficient that denotes the effect of smog pollution level (i.e., the dependent variable) of neighbors in city i. $\boldsymbol{\delta}$ is the spatial coefficient that denotes the possible impact of neighbors' independent variables, and λ is the spatial error coefficient that represents the potential spatial correlation from unobservable random shocks, such as irregular weather changes. v_{it} controls random errors. Other variables and parameters are the same as in Eq. (2).

3.3. Causal mediation analysis

Section 2 divides the impacts of HSR on urban smog pollution into one direct impact and two indirect impact mechanisms (see Fig. 2).

Table 1
Variables, definitions, and descriptive statistics (284 cities' panel data, 2007–2016).

Variable	Description	Obs.	Mean	Min	Max
$\ln PM_{it}$	The log value of $PM_{2.5}$ of city i in each year t.	2840	3.5	1.5	4.5
$HSR_i \times After_t$	The dummy variable denotes whether city i is on HSR network and year t is the year after HSR being in-service.	2840	0.3	0.0	1.0
$\ln A_{it}$	The log value of GDP per capita at constant 2007 prices (CNY).	2840	10.2	8.1	12.2
$\ln P_{it}$	The log value of population (ten thousand).	2840	5.9	3.0	8.0
$\ln T_{it}$	The log value of the ratio of scientific and technical industry employment to total employment (%).	2840	0.2	−2.1	2.3
FDI_{it}	The log value of foreign direct investment at constant 2007 prices (ten thousand CNY).	2840	11.2	0.0	16.7
OPT_{it}	Other passenger traffic, denoted by the ratio of passenger traffic of air, road and water transport to population.	2840	21.2	0.4	328.0
SSU_{it}	Sector structure upgrading, denoted by the ratio of tertiary-industry outputs to secondary-industry outputs.	2840	0.8	0.1	4.2
HOU_{it}	The log value of the sold area of commercial & residential housing.	2840	7.7	4.0	11.0

To study this mechanism, this paper introduces causal mediation analysis:

$$CMT_{it} = \alpha_0 + \alpha_H HSR_{it} + \mu_i + \gamma_t + e_{it} \tag{5}$$

$$\begin{cases} y_{it} = \rho\mathbf{WY} + \mathbf{WX}\boldsymbol{\delta} + \beta_C CMT_{it} + \beta_1{}' HSR_i \times After_t + \beta_2 \ \ln A_{it} \\ \quad + \beta_3 \ \ln A_{it}{}^2 + \beta_4 \ \ln A_{it}{}^3 + \beta_5 \ \ln P_{it} + \beta_6 \ \ln P_{it}{}^2 + \beta_7 \ \ln T_{it} \\ \quad + \beta_8 COV_{it} + \mu_i + \gamma_t + \varepsilon_{it} \varepsilon_{it} = \lambda\mathbf{W}\boldsymbol{\varepsilon} + v_{it} \end{cases} \tag{6}$$

where CMT_{it} denotes the causal mediation term. The main focus is on two kinds of CMT_{it}: sector structure upgrading (SSU_{it}) and real estate development (HOU_{it}). The former is measured by the ratio of tertiary-industry outputs to secondary-industry outputs. HOU_{it} is denoted by the sold area of commodity housing rather than housing prices, considering that the air pollution caused by real estate development comes mainly from the building industry's energy consumption and emissions. In Eq. (5), parameter α_H is the impact of HSR on the CMT_{it} variables; α_0, μ_i, and γ_t are the constant term and the city- and year- fixed effects, respectively. Other variables and parameters are the same as in Eqs. (2) and (4).

The identification strategy of the causal mediations is as follows: first, if the estimate of β_1 in Eq. (4) is negative and significant, the overall effects of HSR on smog control can be confirmed. The second step is to examine the impacts of HSR on CMT, and this study uses an intertemporal difference-in-difference model to test this issue before and after HSR operation. To avoid the omissions that can bias the estimates in a typical cross-sectional study or a typical time-series study, this paper controls the time-invariant variables with city-specific effects μ_i and year-specific effects γ_t. The final step is to compare the regression results of Eqs. (4), (5), and (6). Specifically, if both of the estimations of β_1 and $\beta_1{}'$ in Eqs. (4) and (6) are significant and negative, the respective overall and direct impacts of HSR on smog control are confirmed. Besides, if the estimations of α_H and β_C in Eqs. (5) and (6) are both significant, a certain indirect impact is signified; however, if at least one of the two estimations is not significant, a bootstrap test should be conducted for further checks.

3.4. Variables and data

This study uses a panel data set comprising 284 Chinese cities from 2007 to 2016. China's sixth (most recent) railway speed upgrade was completed in April 2007 for the traditional rail network. Since then, HSR has become an increasingly important form of rail transport in China. The speed of conventional trains has not changed significantly, and the stable travel time between cities offered by railways is guaranteed. Therefore, this paper treats this upgrade as the starting point of this study.

As the 10-year panel data contains 284 cities, each variable has 2840 observations. Table 1 shows the definitions and statistics for the variables in this study. Data on $PM_{2.5}$ are collected from the Socioeconomic Data and Applications Center and calculated according to the method proposed by Van Donkelaar et al. (2015). The data on which HSR operates is collected from the *Chinese Research Data Services Platform* (CNRDS).[1] City-level data on GDP per capita, population, employment, FDI, passenger traffic, and the secondary/ tertiary industry outputs are collected from *China Statistical Yearbook* and *China City Statistical Yearbook*,[2] which are published annually with the local government *Statistical Bulletin*. Data on the sold areas for commercial and residential housing are collected from CEIC Data.[3]

4. Empirical analysis

4.1. Spatial DID analysis results

This study first calculates the Moran's I index year by year, which is the premise for spatial econometrics analysis. As shown in Table 2, urban smog pollution is highly correlated with neighboring cities' performance, with an increasing trend.

Based on Eq. (4), this study examines the impacts of HSR on urban smog pollution with spatial correlations considered. Table 3 reports the general spatial DID regression results. It is worthy to note that two types of city-specific effects are controlled for spatial panel data: fixed effects (FE) and random effects (RE).[4] According to the results of the Hausman test, fixed effects (FE) should be selected. Therefore, Table 3 omits the results with RE to save space.

As shown in Column (1) in Table 3, the spatial autocorrelation and spatial error coefficients are 0.08 and 0.91, respectively, supporting a significant positive spatial correlation of urban smog pollution. This result indicates that the smog pollution in a given city will be significantly affected by its neighboring cities' smog pollution.

HSR has significant negative impacts from $\ln PM_{2.5}$, with a regression coefficient of −0.8%, on average. This supports Hypothesis 1—that is, HSR has a direct effect on reducing smog pollution.

The regression results of other variables are consistent with the expectations outlined earlier. The impacts of per capita GDP and population on smog pollution are nonlinear. Specifically, the square (cubic) term of per capita GDP—that is, $\ln A^2$ ($\ln A^3$)—shows significant negative (positive) impacts on smog pollution, whereas the coefficient of the square term of the population ($\ln P^2$) is significantly positive. The effect of technological progress on smog pollution is not significant.

This paper further controls OPT and FDI, and the regression results with covariates are reported in Column (2) of Table 3. Other passenger

[1] URL: https://www.cnrds.com/.
[2] The database is available at http://data.cnki.net/, with institutional access.
[3] URL: https://www.ceicdata.com/en.
[4] As to the regression results of *constant* (intercept), Elhorst (2012) indicated that if spatial city-specific effect μ_i and/or time-period specific effect γ_t were treated as fixed effects (FE), the intercept could be estimated only under the condition/conditions that $\sum_i \mu_i = 0$ and $\sum_t \gamma_t = 0$; an alternative and equivalent formulation was to drop the intercept from the model and to abandon one of these two restrictions (see Hsiao, 2003, p. 33). Therefore, the intercept is reported when μ_i is treated as a random effect (RE), while it is dropped when treated as a fixed effect (FE).

Table 2
Results of Moran's I index.

Year	2007	2008	2009	2010	2011
Moran's I index	0.676	0.677	0.661	0.677	0.689
Year	2012	2013	2014	2015	2016
Moran's I index	0.682	0.695	0.676	0.719	0.731

Note: *** p < 0.01, ** p < 0.05, * p < 0.1.

Table 3
The general spatial econometrics regression results.

Dependent variable	(1)	(2)
	ln$PM_{2.5}$	ln$PM_{2.5}$
$w^*\ln PM_{2.5}$ (ρ)	0.0863** (0.041)	0.0815** (0.040)
$w^*\varepsilon$ (λ)	0.9125*** (0.010)	0.9142*** (0.009)
$HSR\times After$	−0.0080** (0.003)	−0.0080** (0.003)
ln$A$	0.9540 (0.594)	1.0755* (0.594)
lnA^2	−0.1056* (0.058)	−0.1172** (0.058)
lnA^3	0.0036* (0.002)	0.0040** (0.002)
ln$P$	−0.3660*** (0.112)	−0.3651*** (0.112)
lnP^2	0.0259*** (0.010)	0.0262*** (0.010)
ln$T$	−0.0013 (0.003)	−0.0018 (0.003)
OPT		0.0001** (0.000)
FDI		−0.0024** (0.001)
w^*FDI (δ)		−0.0060** (0.003)
Spillover of FDI		−0.0065** (0.003)
City effects	FE	FE
Year effects	Yes	Yes
Constant		
Observations	2840	2840
Wald test (p)	256.2 (0.000)	266.2 (0.000)
Hausman (p)	291.4 (0.000)	41.7 (0.001)

Notes: 1. Standard errors in parentheses. 2. ***p < 0.01, **p < 0.05, *p < 0.1.

transport significantly increases urban smog pollution, whereas FDI observably reduces smog pollution, with a coefficient of 0.24%. Moreover, the impact of FDI has significant spatial spillovers; that is, FDI can reduce smog pollution locally and in nearby cities.[5] This result may indicate that China has learned advanced technologies and development experiences when attracting FDI, and technology and experience transfer is often regarded as an externality of FDI (Barro and Sala-I-Martin, 2003). This finding may provide some new evidence for the widely discussed heaven or halo hypotheses like Liu et al. (2018) and Xu et al. (2021). Comparing the regression results in Column (2) and Column (1), the coefficients of other independent variables are robust after controlling for the covariates.

Next, this study further discusses the nonlinear effects of per capita GDP and population on smog pollution in an attempt to offer some new explanations. These findings are helpful for enriching the EKC hypotheses. Using the regression results in Column (2) shows that the impact of GDP per capita on smog pollution follows an N-shaped curve (see Fig. 3). The two inflection points of this N-shaped curve are $A_1 = 1581$ *yuan* and $A_2 = 192{,}383$ *yuan* (see Fig. 3). During the sample period (from 2007 to 2016), it is observed that the per capita GDP of most cities lay within the range between the inflection points A_1 and A_2, which means that $PM_{2.5}$ decreases as per capita GDP increases.

However, it is noted that the per capita GDP of two cities, Karamay and Dongying, were on the right side of the second inflection point. That is to say, these two cities exceeded the second turning point, which means that as per capita GDP increases, smog increases. These two cities are known to be resource-based cities with mining and sales of mineral resources regarded as their main pillar industries.

Similarly, the regression results in Column (2) also demonstrate that the impacts of population on smog are nonlinear. Zhao et al. (2016) proposed that the relationship between urbanization and eco-environment showed differentiated inverted-U curves. Unlike Zhao et al. (2016), this paper finds that the relationship between population and smog pollution presents a U-shaped curve (see Fig. 4), which can be explained from the perspective of economies of scale. In the initial stage of urbanization, migrants to cities gradually realize economies of scale because the costs of public services are shared, and the centralized use of energy increases efficiency. As population size expands and exceeds the optimal scale, newcomers need more public service and energy consumption, resulting in aggravating smog pollution.

The inflection point of the U-shaped curve is $P_0 = 10.6$ million (see Fig. 4). During the sample period, 11 main cities had a larger population than P_0, namely, Beijing, Shanghai, Guangzhou, Shenzhen, Tianjin, Chongqing, Shijiazhuang, Baoding, Suzhou, Wuhan, and Chengdu. Other cities are still on the left side of the U-shaped curve.

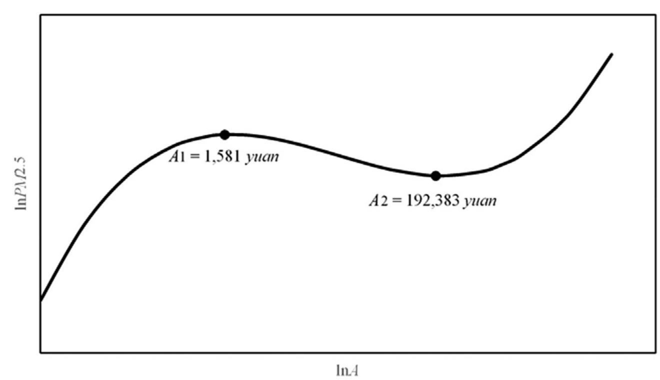

Fig. 3. The N-shape curve of the relationship between per capita GDP and smog pollution.

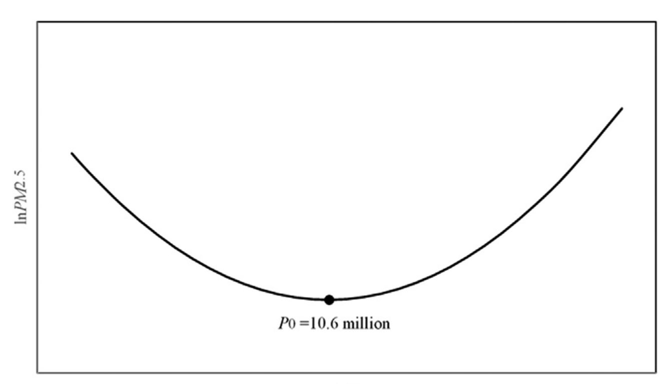

Fig. 4. The U-shape curve of the relationship between population and smog pollution.

[5] This study has also controlled for the spatial correlation terms of other independent variables, but none of them are significant.

4.2. Causal mediation analysis results

Table 4 shows the results from the causal mediation analyses. Columns (1) and (2) report the results concerning the first causal mediation, i.e., sector structure upgrading (*SSU*). Column (1) shows that HSR projects accelerate sector structure upgrading, with an elasticity of 4.21%. Column (2) provides the results of spatial DID analysis with the addition of causal mediation *SSU*. The elasticities of $\ln PM_{2.5}$ with respect to HSR and *SSU* are −0.77% and −1.55%, respectively. These two columns of regression results strongly support Hypothesis 2—that is, sector structure upgrading has mediating effects on urban smog control. Hence, HSR can reduce $\ln PM_{2.5}$ by promoting sector structure upgrading.

The results of the second causal mediation, real estate development (*HOU*), are reported in Columns (3) and (4). As shown in Column (3), the impacts of HSR on *HOU* are positive but not significant. Therefore, a bootstrap test was necessary (see Section 3.3), which found that the bootstrap stand error is significant at the 5% level, supporting that real estate development is a causal mediation of HSR in affecting urban smog pollution. The elasticity of $\ln PM_{2.5}$ with respect to HSR and *HOU* is −0.81% and 0.80%, respectively (see Column (4)), supporting Hypothesis 3—that is, HSR can increase smog pollution by promoting real estate market development.

What is striking in this table is that this aggravation is spatially positively correlated, with spatial spillovers of about 1.85%. The spatial correlations of *HOU* reflect a new choice in China: that is, more and more residents choose to work in developed economic centers but buy houses and live in nearby cities. The reasons for this choice are that (1) housing prices in economic centers are too high to afford, and (2) HSR makes it much easier to travel across cities. For example, for those who work in Shanghai and live in the neighboring city Suzhou, the daily one-way commute time by HSR is less than half an hour, and the cost for a second-class seat is less than $6. HSR has made this work-home location strategy more popular, especially for the younger workforce.

Finally, this paper examines the combined effects of the two causal mediations, and the results of this joint causal mediation are reported in the last two columns of Table 4. The coefficient of the cubic term of per capita GDP in Column (5) is not significant; hence, it was removed to get the regression result in Column (6). Column (6) shows that *SSU* significantly reduces smog pollution with an elasticity of −1.38%, whereas *HOU* notably exacerbates smog pollution, with an elasticity of 0.81%. The elasticity of $\ln PM_{2.5}$ with respect to the interaction of the

Table 4
Results of the causal mediation analysis.

Dependent variable	(1)	(2)	(3)	(4)	(5)	(6)
	SSU	$\ln PM_{2.5}$	*HOU*	$\ln PM_{2.5}$	$\ln PM_{2.5}$	$\ln PM_{2.5}$
$w^*\ln PM_{2.5}$ (ρ)		0.0795**		0.0760*	0.0747*	0.0751*
		(0.040)		(0.040)	(0.040)	(0.040)
$w^*\varepsilon$ (λ)		0.9153***		0.9174***	0.9190***	0.9189***
		(0.009)		(0.009)	(0.009)	(0.009)
HSR×After	0.0421**	−0.0077**	0.0420	−0.0081***	−0.0086***	−0.0089***
	(0.020)	(0.003)	(0.037)	(0.003)	(0.003)	(0.003)
SSU		−0.0155**			−0.0136**	−0.0138**
		(0.006)			(0.006)	(0.006)
HOU				0.0080**	0.0080**	0.0081**
				(0.004)	(0.004)	(0.004)
w^*HOU (δ_{HOU})				0.0171**	0.0191**	0.0191**
				(0.007)	(0.007)	(0.007)
Spillover of *HOU*				0.0185**	0.0205**	0.0206**
				(0.008)	(0.008)	(0.008)
*SSU***HOU*					0.0092***	0.0099***
					(0.003)	(0.003)
$\ln A$		0.9946*		1.0516*	0.6449	−0.2201***
		(0.594)		(0.593)	(0.601)	(0.066)
$\ln A^2$		−0.1116*		−0.1156**	−0.0794	0.0055*
		(0.058)		(0.058)	(0.059)	(0.003)
$\ln A^3$		0.0038**		0.0039**	0.0028	
		(0.002)		(0.002)	(0.002)	
$\ln P$		−0.3871***		−0.3804***	−0.3329***	−0.3398***
		(0.112)		(0.112)	(0.114)	(0.114)
$\ln P^2$		0.0273***		0.0271***	0.0207**	0.0212**
		(0.010)		(0.010)	(0.010)	(0.010)
$\ln T$		−0.0018		−0.0018	−0.0018	−0.0014
		(0.003)		(0.003)	(0.003)	(0.003)
OPT		0.0001**		0.0001**	0.0001**	0.0001**
		(0.000)		(0.000)	(0.000)	(0.000)
FDI		−0.0025**		−0.0026**	−0.0027**	−0.0026**
		(0.003)		(0.001)	(0.001)	(0.001)
w^*FDI (δ_{FDI})		−0.0063**		−0.0065**	−0.0066**	−0.0065**
		(0.001)		(0.003)	(0.003)	(0.003)
City effects	Yes	FE	Yes	FE	FE	FE
Year effects	Yes	Yes	Yes	Yes	Yes	Yes
Constant	0.8016***		7.2527***			
Observations	2840	2840	2840	2840	2840	2840
Wald test (p)		271.8		270.8	286.6	284.3
		(0.000)		(0.000)	(0.000)	(0.000)
Hausman test (p)		588.5		86.2	147.2	148.4
		(0.000)		(0.000)	(0.000)	(0.000)
Bootstrap SE (p)				0.002		
				(0.021)		

Notes: 1. *SSU*, *HOU*, and *SSU***HOU* are centered in columns (5) and (6). 2. Standard errors in parentheses. 3. ***p < 0.01, **p < 0.05, *p < 0.1.

two causal mediations is 0.99%, which indicates that the optimization and upgrading of the service industry stimulate higher demand for commercial and residential housing, thereby further increasing building energy consumption and emissions and ultimately worsening urban smog pollution. After controlling for the mediating effects of *SSU*, and the suppressing effects of *HOU* and *SSU***HOU*, the net effect of HSR, on average, is −0.89%.

4.3. Robustness checks

In this section, the spatial contiguity weighting matrix **W** is replaced with the spatial inverse distance weighting matrix **M**, each element of which is $m_{ij} = 1/\text{distance}_{ij}$. Table 5 reports the results of the robustness checks. The estimates of the quadratic and cubic terms of GDP per capita are not significant; so, they are removed. The spatial correlations of urban smog pollution and the reduction impacts of HSR are significant and highly consistent with the previous regression results.

4.4. Policy recommendations, limitations, and discussions

All of these findings give rise to the following discussions and policy recommendations for China's development:

(1) As already noted, this study finds that most Chinese cities' per capita GDP lies within the range between the two inflection points of the N-shaped curve; that is, smog decreases as per capita GDP increases. To a certain extent, this finding provides evidence for China's effectiveness in controlling smog. However, an increasing number of cities will face the problem of crossing the second infection point and entering a state where smog increases as per capita GDP increases if the current development model and the trends continue. Therefore, the fundamental strategy to control smog pollution is to change the existing development model and optimize its industrial structure.

(2) At the same time, the trend of less smog in cities with high per capita GDP also exposes a city government's decision-making problems in smog governance and economic development. It is a commonly used strategy for pollution control of economically developed cities by relocating their high-polluting industries to nearby underdeveloped areas. And those host cities are either willing to accept such industries for economic development reasons or are forced to accept them under political pressure. This is the case in the Beijing-Tianjin-Hebei urban agglomeration, in which Beijing is the economic center. This strategy is not sufficiently effective because the significant spatial correlation of $PM_{2.5}$ indicates that smog pollution in neighboring cities can increase local pollution. It is necessary as well as essential to improving production technology to control pollutant emissions.

(3) The construction of wider and denser HSR networks is supported because HSR can increase economic and environmental benefits. Moreover, China needs to upgrade the sector structure by increasing the proportion of the service sector, which will help alleviate smog pollution. HSR can make a positive contribution to sector structure upgrading, and this upgrading can also amplify the HSR effects.

(4) China needs to reduce regional development differences and improve the uneven distribution of the population. The population of 11 cities has exceeded the optimal scale, resulting in smog pollution aggravation as the population increases. If this uneven development is not curtailed, more developed cities will exceed the optimal scale, while developing cities will not reach the optimal scale due to population loss. China should develop the developing areas, increase investment in these places, and construct more modern infrastructure—including HSR—to attract population backflow. Such action would have the double benefit of reducing population pressure in developed areas and realizing economies of scale in the developing regions.

Table 5
Results of robustness checks.

Dependent variable	(1)	(2)
	$\ln PM_{2.5}$	$\ln PM_{2.5}$
Spatial weighting matrix	**M**	**M**
$m^*\ln PM_{2.5}$ (ρ)	2.4954***	2.4957***
	(0.043)	(0.043)
$m^*\varepsilon$ (λ)	2.4952***	2.4957***
	(0.043)	(0.043)
HSR×*After*	−0.0098**	−0.0096**
	(0.004)	(0.004)
ln*A*	−0.0048	−0.0002
	(0.021)	(0.021)
ln*P*	−0.2184	−0.2123
	(0.143)	(0.143)
lnP^2	0.0213*	0.0210*
	(0.013)	(0.013)
ln*T*	−0.0006	−0.0007
	(0.004)	(0.004)
COV		Yes
City effects	FE	FE
Year effects	Yes	Yes
Observations	2840	2840
Wald test (p)	7859.4	7868.4
	(0.000)	(0.000)
Hausman test (p)	5710.2	5745.2
	(0.000)	(0.000)

Notes: 1. Standard errors in parentheses. 2. ***p < 0.01, **p < 0.05, *p < 0.1.

In terms of limitations and future prospects, this study introduces causal mediation analysis to test the mechanism whereby HSR affects smog pollution. Though this approach is innovative, it also has limitations because it cannot avoid the endogenous problem caused by omitted variable bias. Despite such limitations, the role of causal mediation analysis in mechanism identification is still affirmed. By comparing the regression results with and without causal mediation variables, this study found that the coefficients of the independent variables, especially HSR, are robust. Therefore, it can be accepted that the impacts of omitted variable bias on this paper are within tolerances.

An enlightening discussion in this paper concerns the new phenomenon, inspired by HSR, that has made cross-city traveling ever faster and more convenient. HSR allows residents in the Yangtze River Delta, one of China's most urban agglomerations, to work in the economic center Shanghai and live in neighboring cities with lower housing prices. The spatial correlation of real estate market development, one of the causal mediations of HSR, provides evidence of this phenomenon. This finding suggests that HSR may be weakening the boundaries between cities and may have more profound impacts on the regional integrated development and comprehensive pollution control. These aspects are worthy of further exploration in future research.

5. Conclusions

This paper finds that HSR can bring positive environmental benefits. In exploring the mechanism of HSR effects (see Fig. 2), two causal mediations are discussed. The first is sector structure upgrading, which has the mediating effect on the tendency of HSR to reduce smog pollution. The second is real estate development, which is stimulated by HSR and, therefore, tends toward an increase in smog pollution. After controlling for the two causal mediations with opposite effects, the net impacts of HSR on smog pollution are negative. In other words, the reducing effects of HSR on smog pollution are higher than its aggravating effects. Another contribution of this study is that it enriches the EKC hypothesis as follows: (1) an N-shaped curve is revealed between per capita GDP and urban smog pollution, and (2) the relationship between population and smog pollution presents a U-shaped curve. These results indicate that China should continue building a denser HSR network, improving the sector structure, and narrowing regional development differences to control smog pollution.

CRediT authorship contribution statement

Jing Fang: Independently undertake all the work of this article.

Declaration of competing interest

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