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Research Article

Effects of Urban Density and City Size on Haze Pollution in China: Spatial Regression Analysis Based on 253 Prefecture-Level Cities $PM_{2.5}$ Data

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Based on the $PM_{2.5}$ concentration data of 253 prefecture-level cities, it empirically investigated the effect of urban density on $PM_{2.5}$ concentration in China using spatial econometric regression method. The results show that there is a spatial spillover effect of $PM_{2.5}$ concentration in China. The coefficient of urban density is significantly negative, and the increase in urban density will reduce haze pollution. In order to reduce haze pollution in Chinese cities, it is necessary to continue to implement regional joint prevention and control measures. The eastern region should focus on building small blocks and high-density networks to reduce haze pollution. The central region should focus on urban greening, increase green coverage, and reduce the heat island effect. While improving the level of greening in the western region, we should increase urban density, reduce urban sprawl, and build compact cities.

1. Introduction

Since 2013, haze pollution has been hanging over Chinese cities. The main components of haze pollution are $PM_{2.5}$ and PM_{10}, of which $PM_{2.5}$ has the greatest impact on the human body. $PM_{2.5}$ aggravates people's fear of haze pollution and seriously affects people's physical and mental health [1, 2]. From January 10 to 15 in 2013, haze pollution caused about 489 million Yuan of losses, more than 90% of which were due to acute bronchitis and asthma [3].

In order to explore the causes of urban haze formation, many literature have deeply analyzed from the perspective of socio-economic development [4]. A large number of studies believe that economic development, urbanization, industrial structure, and energy consumption are the main reasons for the formation of haze [5–13]. These studies recognize that industrial activities in cities are responsible for the formation of haze pollution. In fact, urban development patterns such as urban density, city size, and haze pollution are also related. China's urbanization process has developed rapidly, and the level of urbanization has increased from 17.92% in 1978 to 59.58% in 2018. With the influx of rural population into cities, it is of great practical significance to study the impact of urban density on haze pollution.

In terms of urban density research on air pollution, mainstream economics argues that urban low-density spread exacerbates the challenge of open space protection, leading to poor air quality [14]. Low-density urban sprawl can lead to longer commutes, excessive motor vehicle dependence, and increased emissions, resulting in higher concentrations of air pollutants [15–19]. Ewing et al. studied the impact of low-density urban sprawl on traffic in 83 large cities in the United States from 1990 to 2000. It was found that low-density, motor-oriented urban sprawl is not conducive to the formation of good air quality [20]. Pourahmad et al. studied the adverse effects of urban low-density sprawl on air pollution in megacities such as Tehran, and found that urban low-density sprawl increased air pollution levels [21]. Stone used the data of 45 major cities in the United States from 1990 to 2002 to prove that the urban air pollutants in the urban sprawl exceeded the standard is more serious than that of the compact city. The more compacts the city, the smaller the spread, the more likely it is to reduce air pollution emissions. The cars are the link between numerous mechanisms of environmental degradation caused by urban sprawl [22].

However, there are disputes about the relationship between urban density and air pollution in China. Fan et al. conducted research on 344 prefecture-level cities in China and found that cities in the northern plains of China should be as compact and continuous as possible and polycentric morphology can effectively reduce air pollution emissions [23]. Sun et al. demonstrated through empirical research that rapid urban sprawl in Jinan and Zhengzhou has caused serious particle pollution problems in the past five years [24]. Qin et al. used $PM_{2.5}$ surface concentration data, global nighttime lighting data, LandScan population distribution data, and economic statistics to calculate the sprawl index of cities in China, and empirically analyzed the impact of urban sprawl on haze pollution in prefecture-level cities. The results indicate that urban sprawl will increase the concentration of $PM_{2.5}$ in the local area, and the same direction correlation of urban sprawl and haze concentration will be weakened by the increase of urban scale [25]. Other studies suggest that the compact urban form is not suitable for China's already high-density urban mixed land use [26]. For example, Yuan et al. selected 269 sample cities in China, using $PM_{2.5}$ remote sensing data, and using spatial regression models to explore the impact of urban density on haze pollution. The results show that urban density has a significant positive impact on $PM_{2.5}$. The impact of urban density on $PM_{2.5}$ concentration may depend on population size [27].

The above research laid the foundation for this article, but there are also some shortcomings: Firstly, there is little literature about the impact of urban density on haze pollution and PM_{10} is often used to refer to haze pollution. Secondly, there are fewer literatures about the empirical test of the impact of urban sprawl on haze pollution, which is obviously not conducive to the scientific formulation of policies related to haze pollution control in China. Based on this, this paper puts urban density and haze pollution into a framework, using the data of $PM_{2.5}$ concentration in 253 cities in China. It empirically examines the impact of urban density on haze pollution, and proposes relevant countermeasures to deal with haze pollution in Chinese cities.

2. Methodology and Data

2.1. Model Specification. In order to explore the impact of urban density on haze pollution, the following model is defined based on existing research results:

$$\begin{aligned}\ln\mathrm{PM}_{2.5} = {} & \beta_0 + \beta_1\ln\mathrm{PD} + \beta_2\ln\mathrm{CitSize} + \beta_3\ln\mathrm{GreLevel} \\ & + \beta_4\ln\mathrm{RoadDen} + \beta_5(\ln\mathrm{RoadDen})^2 + \varepsilon.\end{aligned} \tag{1}$$

$PM_{2.5}$ refers to $PM_{2.5}$ concentration; PD is urban density; CitSize refers to city size; GreLevel refers to greening level; RoadDen refers to road density. β_0, β_1, β_2, β_3, β_4, and β_5 are parameters to be estimated by the model. ε is the standard error term and follows a normal distribution $\left(0,\ \sigma^2\right)$. In order to reduce the influence of heteroscedasticity, each variable takes the natural logarithm.

2.2. Spatial Regression Model. This study used the global spatial autocorrelation coefficient Moran's I to assess whether $PM_{2.5}$ concentration is related to geography [28], which laid the foundation for the use of spatial regression models.

This study used a spatial regression model instead of the traditional OLS regression model to analyze the impact of urban density on haze pollution. According to Anselin, the spatial lag model (SLM) and spatial error model (SEM) are the most common in the measurement model considering spatial effects [29].

The spatial lag model (SLM) formula is:

$$Y = \rho WY + X\beta + \varepsilon. \tag{2}$$

The spatial error model (SEM) formula is:

$$\begin{aligned} Y &= X\beta + \varepsilon, \\ \varepsilon &= \lambda W\varepsilon + \mu \end{aligned} \tag{3}$$

Y is an $n \times 1$ dimensional dependent variable vector, X is an $n \times k$ dimensional independent variable matrix, and W is an $n \times n$ dimensional spatial weight matrix. In this paper, a spatial adjacency matrix is used. WY is the vector of the spatial lag dependent variable. ρ is the spatial correlation coefficient, and β is the $k \times 1$ dimensional independent coefficient. ε is a random error term. λ is the spatial residual autocorrelation coefficient, reflecting the degree of influence between adjacent regions. μ is the residual that follows a normal distribution.

According to Equation (1), the spatial lag model SLM formula considering spatial effects is:

$$\begin{aligned}\ln\mathrm{PM}_{2.5} = {} & \rho W\ln\mathrm{PM}_{2.5} + \beta_0 + \beta_1\ln\mathrm{PD} + \beta_2\ln\mathrm{CitSize} \\ & + \beta_3\ln\mathrm{GreLevel} + \beta_4\ln\mathrm{RoadDen} \\ & + \beta_5(\ln\mathrm{RoadDen})^2 + \varepsilon.\end{aligned} \tag{4}$$

The spatial error model (SEM) formula is:

$$\begin{aligned}\ln\mathrm{PM}_{2.5} = {} & \beta_0 + \beta_1\ln\mathrm{PD} + \beta_2\ln\mathrm{CitSize} \\ & + \beta_3\ln\mathrm{GreLevel} + \beta_4\ln\mathrm{RoadDen} \\ & + \beta_5(\ln\mathrm{RoadDen})^2 + \varepsilon, \\ \varepsilon = {} & \lambda W\varepsilon + \mu.\end{aligned} \tag{5}$$

The meaning of each variable in the formulas (4) and (5) is the same as Equations (1)–(3).

The SLM and SEM were run using GeoDa with the maximum likehood (ML) method.

In order to determine whether to use the spatial lag model SLM or the spatial error model SEM, model selection is required [30]. The model is first estimated by least squares (OLS) and then the significance of the Lagrange multiplier LM is compared. If LM-lag is statistically more significant than LM-error, and Robust LM-lag is significantly higher than Robust LM-error, the spatial lag model SLM is used. Conversely, LM-lag is statistically less significant than LM-error, meanwhile, Robust LM-lag is significantly lower than Robust LM-error, using the spatial error model SEM.

Table 1: Descriptive statistics of the variables used in this study.

Variables	Meaning	Unit	Obs	Mean	Min	Max	Std. Dev.
$PM_{2.5}$	$PM_{2.5}$ concentration	$\mu g/m^3$	253	46.569	14.80	86.100	14.259
PD	Urban density	person/km^2	253	3746.170	450.0	11602.00	2415.017
CitSize	City size	10,000 persons	253	119.920	7.720	2418.330	235.602
GreLevel	Greening level	m^2	253	14.294	6.860	37.490	4.036
RoadDen	Road density	km/km^2	253	8.758	1.346	70.298	7.916

Table 2: Correlation matrix between independent variables and VIF tests.

Variable	VIF	$PM_{2.5}$	PD	Citsize	GreLevel	RoadDen
$PM_{2.5}$		1				
PD	1.0951	0.0573	1			
Citsize	1.0189	0.0222	0.0374	1		
GreLevel	1.0953	-0.1179^{*}	-0.2839^{***}	−0.0436	1	
RoadDen	1.0179	0.3355^{***}	−0.0465	−0.1008	−0.0548	1

Note: $*, ***$ represent significance levels of 10% and 1%, respectively.

2.3. Data. The international environmental protection organization Greenpeace released the "2015 China 365 Cities $PM_{2.5}$ Concentration Ranking" published on January 10, 2018 (https://www.greenpeace.org.cn/air-pollution-2017-city-ranking/), 253 prefecture-level cities $PM_{2.5}$ concentration data comes from this. Population density is used to denote urban density. The population density, city size, greening level, total length of urban roads, and the area of urban built-up area, etc., are from the China Urban Construction Yearbook 2017. The road density is calculated by dividing the total length of urban roads by the urban built-up areas. Missing data are filled by interpolation. To sum up, the definitions and the descriptive statistics of the variables utilized in this study are given in Table 1.

The correlation coefficient and multicollinearity test of the variables are shown in Table 2. It can be seen that all the correlation coefficients are lower. Using the variance inflation factor VIF to test for multicollinearity, the results show that all the independent variables' VIF is less than1.1, and the mean value is 1.06. Since the VIF values are all less than 10, there is no multicollinearity.

3. Results and Discussion

3.1. Spatial Patterns of $PM_{2.5}$ Concentrations. The spatial distribution of $PM_{2.5}$ concentration is shown in Figure 1. The eight cities with the most serious haze pollution are Handan, Baoding, Anyang, Shijiazhuang, Xingtai, Hengshui, Jiaozuo, and Luoyang. Among them, five cities are located in Hebei Province and three cities are located in Henan Province. The cities with the least haze pollution are Guangyuan, Yuxi, Heihe, Yichun, Haikou, Hulunbeier, Sanya, and Lijiang. The overall haze pollution in Chinese cities has shown a downward trend from north to south and from east to west.

The global autocorrelation of urban $PM_{2.5}$ concentration is illustrated using Moran's I index scatter plot. As shown in Figure 2, the Moran's I index of urban $PM_{2.5}$ concentration is 0.6879, and the significance test of 1% level is passed, indicating that there is a spatial agglomeration of haze pollution. The first, second, third, and fourth quadrants characterize high-high, low-high, low-low, and high-low agglomerated types, respectively. A large number of cities are located in the first and third quadrants, and only a small number of cities are located in the second and fourth quadrants, that is, the urban $PM_{2.5}$ space presents a high-high and low-low agglomeration mode. It indicates that cities in high-high quadrants have potential strong pollution spillover to neighboring cities; On the contrary, cities in low-low quadrants have low pollution agglomeration to neighboring cities, which provides a basis for the use of spatial regression model.

3.2. Results of the Regressions. Based on the spatial autocorrelation analysis above, the OLS model and the Lagrange Multipliers LM-lag, LM-error, Robust LM-lag, and Robust LM-error are used to select the spatial econometric model. The results are shown in Table 3. The Lagrange multiplier (LM) and robust LM tests for the SLM and SEM are significant, and these two spatial regression models are both used in the following estimations.

The results of spatial regression at the national level are shown in Table 4. Model 1 is the regression result of population density, city size, and greening level on $PM_{2.5}$ concentration. Model 2 increases the regression result of road density, and Model 3 adds the regression result of road density. Models 1–3 shows that the R^2 of the spatial error model SEM is larger than the spatial lag model SLM, and the coefficient of the spatial error model SEM is better than the spatial lag model SLM. Therefore, in the following the estimation results of the spatial error model SEM are used for analysis.

The spatial autocorrelation coefficient λ of $PM_{2.5}$ concentration is significant at the 1% level, indicating that $PM_{2.5}$ is spatially dependent. Moreover, λ is greater than 0.84,

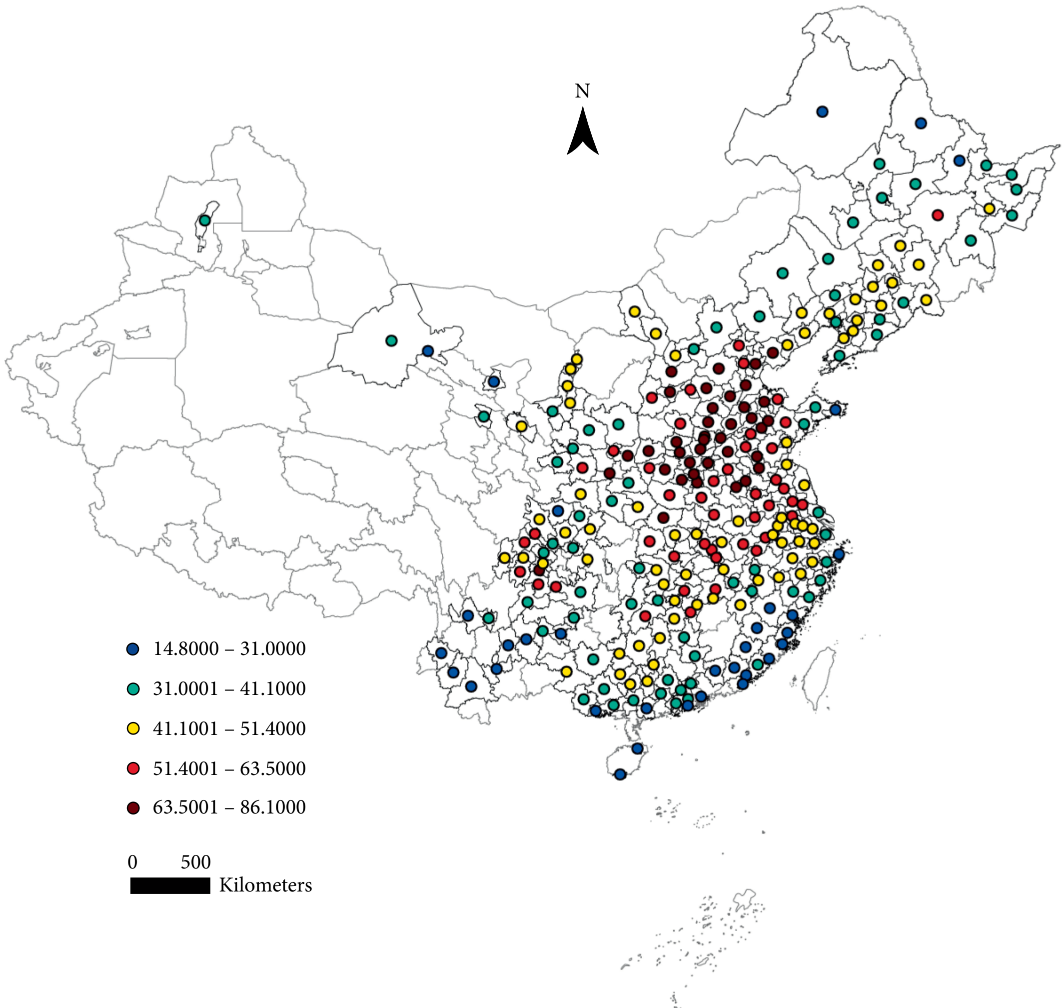

Figure 1: The spatial distribution of $PM_{2.5}$ concentrations.

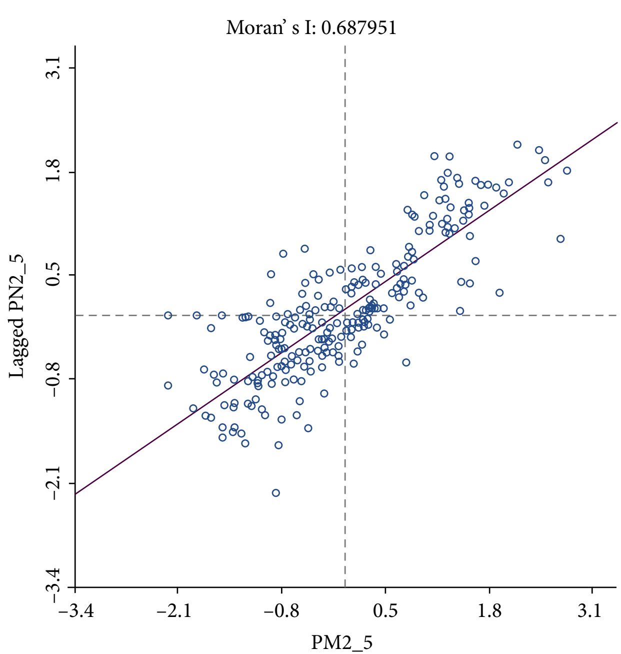

Figure 2: Moran's I index scatter plot of $PM_{2.5}$ concentrations in China.

indicating that the $PM_{2.5}$ concentration spatial spillover effect is obvious, and the adjacent city $PM_{2.5}$ increases by 1%, which will increase the local city's $PM_{2.5}$ concentration by about 0.84%. This is consistent with the Moran's I index scatter plot of Figure 2, that is, there is a significant spatial positive autocorrelation of $PM_{2.5}$ in Chinese cities.

In Models 1–3, the coefficient of urban density is significantly negative, and the increase of urban density reduce will haze pollution, which is consistent with Stone [22]. That is, a compact city is conducive to reducing urban haze pollution in China. Because the compact urban form helps to shorten the travel distance and reduce residents' dependence on the car [14]. The coefficient of city scale is significantly positive, indicating that the city size has a positive impact on haze pollution, that is, the larger the city size, the higher the degree of haze pollution. Based on the empirical results of urban density and city size, it can be seen that for cities of the same size, the higher the urban density, the lower the degree of haze pollution. A compact city is more conducive to mitigating haze pollution than a low-density city. Building a small and compact city is conducive to the management of haze pollution in Chinese cities. For large cities, a multi-center urban form should be built. The coefficient of the greening level is significantly negative, indicating that the improvement of urban

Table 3: Results of the OLS estimation.

Variable	Coefficient	Probability	Spatial dependence	Value	Probability
β_0	3.6543	0.0000	R^2	0.1543	
lnPD	0.0189	0.5302	Log likelihood	−50.0215	
lnCitsize	0.0705	0.0005	LM-lag	64.3114	0
GreLevel	−0.1152	0.0760	Robust LM-lag	30.6144	0
lnRoadDen	−0.1818	0.1748	LM-error	Infinity	0
$(\text{lnRoadDen})^2$	0.0837	0.0040	Robust LM-error	Infinity	0

Table 4: Results of spatial regressions.

Variable	Model 1		Model 2		Model 3	
	SLM	SEM	SLM	SEM	SLM	SEM
ρ	0.1883^{***} (0.0000)		0.2088^{***} (0.0000)		0.1922^{***} (0.0000)	
λ		0.8503^{***} (0.0000)		0.8466^{***} (0.0000)		0.8488^{***} (0.0000)
β_0	2.8975^{***} (0.0000)	4.0379^{***} (0.0000)	2.4456^{***} (0.0000)	3.9278^{***} (0.0000)	2.823^{***} (0.0000)	4.2338^{***} (0.0000)
lnPD	0.0253 (0.3634)	-0.0358^{*} (0.0543)	0.0235 (0.3661)	-0.0339^{*} (0.0688)	0.0266 (0.3136)	-0.0352^{*} (0.0528)
lnCitsize	0.0292 (0.1033)	0.0326^{***} (0.0065)	0.0597^{***} (0.0005)	0.0370^{***} (0.0029)	0.0683^{***} (0.0001)	0.0436^{***} (0.0004)
lnGreLevel	−0.0384 (0.5192)	-0.1429^{***} (0.0003)	−0.0690 (0.2123)	-0.1344^{***} (0.0008)	-0.0961^{*} (0.0910)	-0.1615^{***} (0.0000)
lnRoadDen			0.1595^{***} (0.0000)	0.0301 (0.1956)	−0.1453 (0.2158)	-0.2090^{***} (0.0051)
$(\text{lnRoadDen})^2$					0.0704^{***} (0.0054)	0.0538^{***} (0.0007)
R^2	0.2595	0.6607	0.3545	0.6616	0.3325	0.6768
Log likelihood	−33.7889	30.7763	−17.2486	31.6051	−20.3827	37.1094

Note: *,*** represent significance levels of 10% and 1%, respectively.

greening level could reduce haze pollution. In model 3, the coefficient of road density is significantly negative, and the coefficient of the square of road density is significantly positive, indicating that there is a *U*-shaped curve between road density and haze pollution. That is, in the initial stage of urban development, urban haze pollution will decrease as the road density increases. When the road density increases to a certain level, the haze pollution level will increase as the road density increases. This is also related to city size. When the city size expands, the length of the road will be increased, which will improve the distance between work and living of urban residents, and the commuting time of urban residents will be prolonged. When public transportation fails to fully adapt to the expanded and dispersed urban space, people will rely more on private cars, which will consume more fossil energy and generate exhaust emissions, especially $PM_{2.5}$ emissions. At the same time, the increase of private cars is also likely to cause serious traffic congestion. When traffic jams, gasoline is not completely burned, and it is easy to form haze weather. In addition, the expansion of city size is often accompanied by the increase of urban population agglomeration, which will lead to the expansion of residents' consumption. In order to seize the consumer market of residents and make profits, enterprises in cities will expand production scale, invest in factories, increase resource consumption, and aggravate haze pollution.

China is a vast area and is divided into three regions: the eastern, central, and western regions. Therefore, this paper divides 253 cities into three regions, including 94 cities in the eastern region, 93 cities in the central region, and 66 cities in the western region. The effect of urban density on the $PM_{2.5}$ concentration in the three regions is shown in Table 5.

The regression results of the spatial econometric model show that the spatial error model SEM of the three regions is better than the spatial lag model SLM, so the estimation results of the spatial error model SEM are used for analysis. The spatial autocorrelation coefficients λ of $PM_{2.5}$ concentrations in the eastern, central, and western regions are significantly negative, that is, there is a spatial spillover effect of haze pollution in the three regions. The coefficient of urban density in the eastern and central regions is negative, but not significant, indicating that the impact of urban density on haze pollution

Table 5: Results of spatial regressions in different regions.

Variable	Eastern		Central		Western	
	SLM	SEM	SLM	SEM	SLM	SEM
ρ	0.1835*** (0.0000)		0.7937*** (0.0000)		0.0573*** (0.0000)	
λ		0.8905*** (0.0000)		0.8079*** (0.0000)		0.5645*** (0.0000)
β_0	2.8579*** (0.0000)	3.6008*** (0.0000)	0.7879** (0.0424)	4.0867*** (0.0000)	3.7113*** (0.0000)	4.7008*** (0.0000)
lnPD	−0.0190 (0.6872)	−0.0112 (0.7149)	−0.0151 (0.5860)	−0.0159 (0.5413)	−0.0258 (0.6092)	−0.0763*** (0.0468)
lnCitsize	0.0613 (0.0356)	0.0200 (0.2825)	0.0457** (0.0304)	0.0287 (0.1493)	0.1171*** (0.0004)	0.1076*** (0.0000)
ln GreLevel	0.0839 (0.4951)	0.0391 (0.6836)	−0.0672 (0.1551)	−0.0949* (0.0575)	−0.1217 (0.2559)	−0.2368*** (0.0085)
lnRoadDen	−0.2911 (0.1957)	−0.3404** (0.0262)	0.0375 (0.7057)	−0.0461 (0.6081)	−0.2885 (0.4233)	−0.2520 (0.3587)
$(\text{lnRoadDen})^2$	0.1075** (0.0183)	0.0822*** (0.0071)	0.0082 (0.6913)	0.0200 (0.2772)	0.1044 (0.3204)	0.0615 (0.4431)
R^2	0.4396	0.7370	0.7100	0.7138	0.2900	0.5201
Log likelihood	−9.9659	13.3707	37.5661	36.6526	−1.5504	7.1967

Note: *,**,*** represent significance levels of 10%, 5%, and 1%, respectively.

is not significant in these two regions. The urban density in the western region is significantly negative, and the increase in urban density in the western region will effectively reduce haze pollution. The coefficient of the city size of the eastern and central regions is positive, but not significant, indicating that the impact of city size on urban haze pollution in these two regions is not obvious. The coefficient of city scale in the western region is significantly positive, indicating that the expansion of the scale of western cities has a positive impact on haze pollution. The coefficient of greening level in the eastern region is positive, but not significant. The coefficient of greening level in the central and western regions is significantly negative, and the improvement of greening level in the central and western region could effectively reduce haze pollution. The coefficient of road density in the eastern region is significantly negative, and the square of the road density is significantly positive, indicating that there is a *U*-shaped relationship between road density and haze pollution in the eastern region. The increase in road density will bring about haze pollution, so the eastern region is more suitable for the development of small blocks, high-density network traffic mode.

4. Conclusions and Implications

Haze pollution is an urgent problem to be solved in Chinese cities. An in-depth understanding of the impact of urban density on haze pollution could provide guidance for urban planning. In this study, the $PM_{2.5}$ data of 253 prefecture-level cities in China were used, and the spatial regression model was used to deeply analyze the influence of urban density on $PM_{2.5}$ concentration. The main conclusions are as follows:

(1) The haze pollution in Chinese cities decreased from north to south and from east to west on the whole. In addition, the spatial spillover effect of $PM_{2.5}$ concentration in Chinese cities is obvious and the $PM_{2.5}$ concentration in adjacent cities increase by 1%, which will increase $PM_{2.5}$ concentration in this city by about 0.84%.

(2) The coefficient of urban density is significantly negative, and the increase in urban density will reduce haze pollution. The coefficient of the city scale is significantly positive, and the city size has a positive impact on haze pollution. The larger the city size, the higher the degree of haze pollution. The coefficient of the greening level is significantly negative, and the improvement of urban greening level could reduce haze pollution. There is a *U*-shaped relationship between road density and haze pollution.

(3) The spatial autocorrelation coefficient λ of $PM_{2.5}$ concentration in eastern, central, and western regions is significantly negative, that is, there is spatial spillover effect of urban haze pollution in three regions. The urban density of western region is significantly negative, and the increase of urban density of the western cities will significantly reduce haze pollution. The coefficient of the city scale of the western region is significantly positive, indicating that the expansion of the city scale of western region has a positive impact on haze pollution. The coefficient of greening level in the central and western regions is significantly negative, and increasing the greening level in the central and western cities can effectively reduce haze pollution. The coefficient of road density of the eastern region is negative, and the square of the road density is significantly positive, indicating that there is a *U*-shaped relationship between road density and haze pollution in the eastern region.

Based on the above conclusions, in order to reduce the haze pollution in Chinese cities, the following policy implications are derived: urban haze pollution has a spatial spillover effect, and for cities with severe haze pollution, it is necessary to continue to implement regional joint prevention and control measures; Small and compact cities are more conducive to alleviating haze pollution than low-density sprawl cities. This is because compact cities could shorten the occupational distance of residents, promote residents to decrease the use of cars, and reduce $PM_{2.5}$ concentration. For large cities, multi-center forms can be developed. It is necessary to improve the greening level of the city, enhance the inherent purification and adjustment capabilities of the ecological ring system so that the ecosystem can absorb and degrade air pollutants in time, and reduce haze pollution. We should accelerate the development of small block areas, high-density network traffic modes, reduce road density, improve the efficiency of transportation facilities, and reduce haze pollution. For the three regions, the eastern region has a high level of economic development. It is necessary to focus on building small blocks and high-density networks to reduce haze pollution. The central region should focus on urban greening, increase green coverage, and reduce the heat island effect. While improving the level of greening in the western region, we should increase urban density, reduce urban sprawl, and build compact cities.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Additional Points

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Conflicts of Interest

The author declares that they have no conflicts of interest.

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