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The Influence of Urban Sprawl on Air Pollution and the Mediating Effect of Vehicle Ownership

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Abstract: Based on the panel data of 224 prefecture-level and above cities in China from 2003 to 2016, this paper empirically studies the impact of urban sprawl on air pollution and introduces a mediating effect model to test the mediating role of vehicle ownership concerning the impact of urban sprawl on air pollution. The research in this paper arrives at three conclusions. First, urban sprawl has a significant positive effect on air pollution, and this conclusion is still valid after solving the endogeneity problem and conducting a robustness test. Second, the results of mediating effect test show that urban sprawl indirectly affects air pollution through the partial mediating effect of vehicle ownership. By removing the mediating effect, urban sprawl has a significant negative impact on air pollution, indicating that the mediating effect of vehicle ownership is higher concerning the impact of urban sprawl on air pollution. Third, further panel quantile regression results show that the higher the level of air pollution, the weaker the mediating effect of vehicle ownership and the stronger the direct effect of urban sprawl on air pollution. These conclusions can provide some empirical support for solving the air pollution problems caused by urban sprawl in China.

Keywords: urban sprawl; car ownership; air pollution; mediation effect

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1. Introduction

Over the past 40 years, and more since reform and opening up, China's urbanization process has been accelerating, with the urbanization rate rising from 17.9 percent in 1978 to 60.6 percent in 2019. Urban sprawl plays an important role in driving China's economic development and improving people's wellbeing. However, the excessive growth of urban space has brought about a series of negative problems, such as urban space mismatch, land abuse, traffic deterioration, environmental pollution and so on. According to the 2019 Bulletin on the State of China's Ecology and Environment, 180 of the country's 337 cities exceed the standard for ambient air quality.

Although the relationship between urban sprawl and air pollution draws much attention, the exact path through which urban sprawl affects air pollution remains unclear. The main reason is that there is a complexity and diversity of sources of air pollution. In our paper, our main concern is about the vehicle exhaust emissions, which have been widely proven to be a main source. Specifically, urban sprawl leads to an increase in both commuting distance and commuting time, which in turn leads to increased car ownership among residents and causes more and more atmospheric emissions. However, we lack empirical tests on the pollution effects of the above path. In view of this, this paper focuses on the econometrics analysis of how urban sprawl affects air pollution, and what role car ownership plays in it.

2. Literature Review

2.1. Impact of Urban Sprawl on Air Pollution

Urban sprawl can affect air pollution in many ways, and the significant correlation between the two is widely recognized in the academic community, but the correlation between the two is not clear. Many scholars believe that urban sprawl exacerbates air pollution. For example, urban sprawl will destroy the vegetation around the city, thus reducing the role of vegetation in reducing haze and dust [1,2]. Urban permeable surface will affect urban air circulation to a certain extent, and then affect the diffusion and agglomeration of haze pollution [3]. Holden E and Ingrid T took American cities as samples for research, and found that urban sprawl affected urban energy consumption and thus environmental quality, and cities with sprawl had higher $PM_{2.5}$ emissions [4]. Many scholars have also performed analysis from the perspective of transportation, pointing out that urban sprawl will change residents' travel mode, increase the utilization rate of private cars and further aggravate air pollution [5–7].

There are also many scholars who hold the opposite attitude. For example, the multi-center layout of a city can effectively alleviate traffic congestion, reducing pollution emissions to a certain extent [8,9]. Urban sprawl will lead to a change in industrial structure, and the rationalization of industrial structure and the rapid development of the service industry are conducive to the alleviation of environmental pollution [10]. Urban and economic expansion can promote the sharing of resources and the spillover of knowledge, thus promoting the progress of green technology, realizing the introduction of advanced production equipment and advanced technology, and playing the role of energy conservation, emission reduction and green development [11,12].

In addition, some scholars have concluded that the relationship between urban sprawl and air pollution is not linear, but non-linear. For example, Yang and Yan point out that there is an inverted U-shaped relationship between urban sprawl and haze pollution, and in addition, the impact of urban sprawl on air pollution has significant temporal and regional differences. Feng and Wang's research shows that the relationship between urban sprawl and haze pollution presents a U-shaped relationship in big cities, while an inverted U-shaped relationship in small- and medium-sized cities [13,14].

2.2. Research on Car Ownership

The number of people owning cars in China has risen sharply in recent years, a phenomenon many scholars attribute to urban sprawl caused by rapid urbanization. With the expansion of city scale, people's dependence on private cars gradually increases, and the number of private cars also increases [15–17]. The expansion of low-density urban space will make the areas within the city more dispersed, so that economic activities will spread from the city center to the surrounding cities, and then form a multi-city center, making people more dependent on private cars for travel [18,19]. In addition, the increase in urban population size and income level will increase people's demand for private cars; the decrease in automobile price and the increase in automobile supply will play an important role in promoting people's automobile consumption [20,21], which is also an important factor affecting automobile ownership.

However, the rising rate of car ownership will lead to increased fuel consumption and exacerbate air pollution. According to Wang Li's research, there is a significant positive correlation between private car ownership and pollution index [22]. Li Gong concluded that there was a positive correlation between vehicle ownership and environmental pollution and proposed that controlling vehicle ownership was conducive to improving environmental quality [23]. Since serious air pollution will do great harm to human health, scholars have studied how to effectively solve the environmental problems caused by car ownership. Zhong-fu Tan et al. compared the energy consumption of electric cars and the pollutant emission of fuel vehicles and found that the use of electric cars can reduce pollution emissions and is an effective method for improving urban air quality [24]. Gao et al. empirically measured the influence of gasoline consumption tax on carbon dioxide emissions from private cars and the influencing channels. The results show that a gasoline consumption tax has an inhibiting effect on carbon dioxide emissions, and taxes and fees can affect carbon dioxide emissions through the use of private cars. A gasoline consumption tax also has a certain inhibitory effect on the emission of other air pollutants, which is slightly smaller than that of carbon dioxide emissions. Therefore, an appropriate increase in a gasoline consumption tax can reduce emissions [25].

To sum up, the existing literature has confirmed a significant relationship among urban sprawl, vehicle ownership and air pollution, but no study, based on empirical facts, has specifically studied the role of vehicle ownership concerning the impact of urban sprawl on air pollution. Using 2003–2016 data of more than 224 of China's prefecture-level and above cities, this paper explores how urban sprawl influences air pollution and the role car ownership plays in that process.

3. Mechanism Analysis and Research Hypothesis

3.1. The Influence Mechanism of Urban Sprawl on Air Pollution

Urban sprawl affects air pollution mainly through the depolymerization effect on the city center, the agglomeration effect on the urban fringe and the crowding out effect.

To begin with, the depolymerization effect on the urban center mainly refers to how the economic subjects and related economic activities in the original urban center are transferred from the urban center to the periphery due to urban sprawl, thus avoiding the aggravation of air pollution caused by excessive concentration. The influence mechanism can be analyzed from the following two aspects. The first is from the perspective of pollutant emission, in which the main economic activities of the city center move to the periphery, thereby reducing the domestic and production pollutants of the urban center. Traffic pressure in the city center is also alleviated, resulting in a reduction in air pollution emissions from vehicles. The second is from the perspective of pollutant diffusion. First, the ecological environment of the city center is improved, and the purification and absorption capacity of air pollution are enhanced. Second, the continuous outward expansion of the built-up area and the outward migration of economic activities expand the scope of pollutant diffusion, reducing the number of pollutants that need to be purified and absorbed per unit area, which is conducive to the alleviation of air pollution.

In addition, the agglomeration effect of the urban fringe is relative to the agglomeration effect of the urban center, which means that economic subjects and related economic activities are constantly agglomerating to the urban fringe due to urban sprawl, which aggravates air pollution. First, when the population and economic activities at the edge of the city gather to a certain extent, the edge of the city will become a new city center, which will lead to a continuous increase in production pollutants, household pollutants and exhaust gas emissions of transportation vehicles, thus aggravating air pollution. Second, with the large-scale development of urban fringe areas, cultivated land and woodland areas are constantly transformed into industrial land, which weakens the ability of urban fringe to purify and absorb air pollution and increase industrial pollution.

Finally, there is the crowding out effect of urban sprawl. The crowding out effect runs through the whole process of urban sprawl. Urban sprawl will consume a large amount of land resources. Farmlands, wetlands and forests will be replaced by modern buildings and industries, which weakens the self-regulation and cleaning ability of the atmosphere and aggravates air pollution.

In conclusion, the central disaggregation effect of urban sprawl is conducive to reducing air pollution, while the marginal agglomeration effect and crowding out effect of urban sprawl will aggravate air pollution. The ultimate impact of urban sprawl on air pollution depends on the comparison of the two effects.

3.2. Mediating Effect of Urban Car Ownership on Air Pollution

Urban sprawl will lead to urban spatial differentiation and lag of public transport, which will increase people's dependence on private car travel and eventually lead to an increase in car ownership. First of all, an important manifestation of urban sprawl is the decentralization of urban forms and the single regional function pattern, which leads to the separation of functions, such as employment, housing and entertainment, and makes people rely heavily on private cars for their daily activities. In addition, as cities expand, the suburbs offer relatively cheap housing, which in turn induces people to give up the convenience of work, as well as increasing reliance on cars.

Secondly, the main characteristics of urban sprawl and expansion are "step type", "pie type" and "enclave type". These expansion modes lack systematic planning, and people excessively pursue the economic benefits brought by land development, while ignoring the essence of cities. Urban land is expanding too fast and public transport systems soon fall behind the pace of development. As a result, people's reliance on private cars in daily traffic has increased.

There are direct and indirect ways that an increase in car ownership can affect air pollution. The direct impact is that vehicle exhaust emissions will increase with the increase in vehicle ownership, thus aggravating air pollution. The indirect effect is that the increase in car ownership will increase the traffic burden on urban roads, which in turn will lengthen commuting time and even cause traffic jams. Second, low-speed driving will lead to low fuel combustion efficiency, and increase energy consumption. Moreover, cars at low speeds tend to produce incomplete fuel consumption, which produces more harmful gases and further aggravates air pollution.

To sum up, urban sprawl leads to an increase in car ownership, which in turn exacerbates air pollution. Therefore, a hypothesis is proposed hereby: car ownership plays an intermediary role between urban sprawl and air pollution, and urban sprawl aggravates air pollution by increasing car ownership.

4. Data, Variables and Models

4.1. Data Sources

In this paper, the panel data of 224 prefecture-level and above cities in China from 2003 to 2016 are used. The data are mainly from the China Statistical Yearbook, the China Regional Statistical Yearbook, the EPS database and Wind database, as well as statistical yearbooks and statistical bulletins of various cities.

4.2. Model Setting and Variable Description

Based on the methods proposed by Baron and Kenny [26] and Wen et al. [27], a mediating effect model was built to test the direct and mediating effects of urban sprawl on air pollution:

$$\mathrm{lnPM2.5_{it}} = \alpha_0 + \alpha_1 \mathrm{sprawl_{it}} + \alpha_2 \mathrm{M_{it}} + \mu_i + v_t + \varepsilon_{\mathrm{it}} \tag{1}$$

$$\mathrm{lncar_{it}} = \beta_0 + \beta_1 \mathrm{sprawl_{it}} + \beta_2 \mathrm{W_{it}} + \mu_i + v_t + \theta_{\mathrm{it}} \tag{2}$$

$$\mathrm{lnPM2.5_{it}} = \gamma_0 + \gamma_1 \mathrm{sprawl_{it}} + \gamma_2 \mathrm{lncar_{it}} + \gamma_3 \mathrm{M_{it}} + \mu_i + v_t + \sigma_{\mathrm{it}} \tag{3}$$

In the formula, *i* and *t* are city and time, respectively; α_x, β_x and γ_x are the coefficients of each variable; $\mathrm{lnPM_{2.5}}$ stands for air pollution; sprawl represents urban sprawl; lncar represents the number of cars; and M and W represent the control variables affecting air pollution and vehicle ownership, respectively. In addition, $\varepsilon_{\mathrm{it}}$, θ_{it} and σ_{it} represent the random disturbance term, respectively; μ_i represents the urban individual fixed effect; and v_t stands for time fixed effect.

Equation (1) is used to test whether urban sprawl influences air pollution, and Equation (2) is used to test whether the effect of urban sprawl on car ownership is significant. Equation (3) is used to test the influence of urban sprawl on atmospheric pollution, as well as whether the effect of car ownership on atmospheric pollution is significant.

If α_1, β_1, γ_2 and γ_1 are significant, there is a partial mediating effect; if α_1, β_1 and γ_2 are significant but γ_1 is not, there is a complete mediation effect.

The explained variable is the air pollution index ($\mathrm{lnPM_{2.5}}$ (smog concentration [$\mathrm{PM_{2.5}}$] data is from the Center for Social and Economic Data and Applications [SEDAC] of Columbia University International Earth Science Information Network [CIESIN] published relevant data. These data are based on the aerosol optical thickness [AOD] measured by the Moderate Resolution Imaging Spectroradiometer [MODIS] and Multi-Angle Imaging Spectroradiometer [MISR] onboard the satellite, which is converted into raster data to measure the global haze concentration [$PM_{2.5}$])). Here, the urban $PM_{2.5}$ air pollution index is adopted to reflect the pollution degree of the urban air environment. In order to eliminate certain heteroscedasticity, $PM_{2.5}$ is treated logarithmically.

The explanatory variable is urban sprawl (sprawl). Based on the measurement method of Hong Shijian and Zhang Jingxiang [28], this paper uses the ratio of urban built-up area (municipal district) to the population of the municipal district to represent urban sprawl.

The mediating variable is vehicle ownership (lncar). In this paper, the occupancy of civil automobiles is used to represent the occupancy of automobiles. The occupancy of civil automobiles can better reflect the changes in automobile consumption, which is more consistent with the subject studied in this paper.

The first control variable in Equation (2) is gross domestic product (lngdp), which can reflect the level of urban development to a certain extent. The data were treated at parity with 2003 as the base period, and logarithmic treatment was carried out to eliminate certain heteroscedasticity. The second control variable is road refreshed degrees (lnrrd). In this paper, the ratio of urban highway length (km) to civil vehicle ownership (ten thousand) is used to calculate, which can reflect the degree of traffic congestion in a city. Traffic congestion is also one of the important factors that affect people's choice of buying a car. The third control variable is consumer price index (cpi), which reflects the changes in the price level; the income level of people in the short term will not greatly change, so the consumer price index to a certain extent can reflect the change in residents' actual income level. The fourth control variable is public transportation level (bus). Considering that many public transportation modes are not popular and public buses are relatively well developed, this paper uses the number of buses per 10,000 people to reflect the traffic level, and the ratio of the number of buses (cars) to the population (10,000 people) in the municipal district to calculate. As a substitute for private cars, public transportation has a certain influence on whether people buy cars or not. The fifth control variable is the population of the municipal districts (lnpomd). As far as cars are concerned, people are the most direct influencing factor. Therefore, population will have an impact on car ownership.

The first control variable in Equations (1) and (3) is gross domestic product (lngdp), which is consistent with the description in Equation (2) and reflects the level of urban economic development through the gross domestic product. The second control variable is the added value of the second industry (lnvasi), The increase in the secondary industry leads to the increase in exhaust gas emissions, which further aggravates air pollution. The third control variable is the consumer price index (cpi), which is consistent with the statement in Equation (2). When the consumer price index rises, it means that people's real income level falls. This will affect People's Daily consumption; more consumption is required to meet the daily needs, and the awareness of environmental protection is reduced. The fourth control variable is the road refreshed degrees (lnrrd), a detailed explanation of which was introduced in Equation (2). Congested traffic creates more exhaust emissions. Therefore, the improvement in driving conditions can decrease the amount of air pollution. An increase in road comfort, however, essentially comes from adding more road, which increases the distance people travel daily. In addition, in order to avoid congested roads, people will choose longer driving routes, which will increase their travel distance, resulting in more fuel consumption, more fuel and more air pollution. The fifth control variable is investment in fixed assets (iif), which is calculated by the proportion of fixed asset investment in the GDP.

Table 1 shows the descriptive statistical results of variables, with sample observation values of about 3136. Among them, the mean value of $lnPM_{2.5}$ was 3.5571, and the corresponding level was about 35.01 $\mu g/m^3$, slightly higher than the concentration limit (35.00 $\mu g/m^3$) stipulated in China's Ambulent Air Quality Standard (GB3095-2012). Sprawl and lncar correspond to core explanatory variables. From the mean value, sprawl index shows that the built-up area per 10,000 people is 0.79 km^2. As to the lncar index, the mean value was 12.05, indicating that the average vehicle ownership in prefecture-level regions in China reached 171,133.6.

Table 1. Descriptive statistics of variables.

Scheme	Label	Unit	Observations	Mean Value	Standard Deviation	Minimum	Maximum
$lnPM_{2.5}$	Atmospheric pollution	μg/m^3	3136	3.5571	0.4517	1.5079	4.4702
sprawl	Urban sprawl	km^2/ten thousand people	3136	0.7923	0.3553	0.1048	2.2240
lncar	Car ownership	car	3135	12.0502	1.1767	7.8268	15.5174
lnpomd	Population of municipal district	Ten thousand people	3136	4.6223	0.7766	2.6448	7.8034
lnrrd	Road refreshed degrees	km/ten thousand cars	3128	6.1995	0.9618	3.2655	8.7727
lngdp	Gross Domestic Product	CNY ten thousand	3134	14.2033	1.1531	11.3472	18.3054
lnvasi	Value added by the secondary industry	CNY ten thousand	3133	13.4675	1.2228	10.1495	17.3749
iif	Investment in fixed assets	1	3129	0.6601	0.2877	0.0238	2.3360
cpi	Consumer price index	1	3062	102.7209	2.0355	97	121.2
bus	Public transport level	Car/ten thousand person	3124	6.6605	4.5213	0.2353	55.5619

Note: each of the above units is correspond to the level value of the variables.

5. Empirical Analysis

5.1. Benchmark Regression Analysis

The baseline regression results are shown in Table 2. First, Equation (1) is a regression to test whether the regression coefficient between urban sprawl and air pollution is significant. As shown in Column (1) in Table 2 below, the regression coefficient of urban sprawl is significantly positive at the level of 5%, indicating that there is a significant positive correlation between urban sprawl and air pollution.

In view of the significant urban sprawl coefficient in Equation (1), this paper further tests the mediating effect. The regression results of Equation (2) are shown in Column (2) in Table 2 below. As shown in Table 2, the regression coefficient of urban sprawl is significantly positive at the 1% level, which indicates that urban sprawl has a positive impact on vehicle ownership—that is, with the deepening of urban sprawl, vehicle ownership will gradually increase. The results support the hypothesis. The deepening of urban sprawl, on the one hand, will increase people's traffic demand; on the other hand, the rapid expansion of urban space will lead to the lag of the urban public transport system, which makes people more dependent on private cars to travel. All this will eventually lead to an increase in car ownership.

The following are the regression results of the control variables. The coefficient of GDP is also significantly positive at the 1% level. The coefficient of road refreshed degrees is significantly negative at the 1% level, indicating that a comfortable traffic environment will lead to a decrease in car ownership. Consumer price index at 1% level of significant is positive, such that the price will have a positive influence on car ownership. The coefficient of public transport level is significantly positive at the 1% level, indicating that the improvement in public transport level will have a positive impact on car ownership. This may be because the improvement in the existing public transport level is not enough to meet the current demand of the people. Although the level of public transport has improved, people's reliance on private cars has not changed substantially. In addition, the improvement in public transportation can reflect the improvement in urban traffic operation systems, more orderly road traffic, continuous improvement in traffic efficiency and the continuous optimization of traffic environment. Therefore, it may increase people's preference for buying cars, thus leading to an upward trend of car ownership.

Table 2. Empirical results of model 1, model 2 and model 3.

	(1) $\ln PM_{2.5}$	(2) lncar	(3) $\ln PM_{2.5}$
sprwal	0.0320 ** (0.0142)	0.9190 *** (0.0750)	−0.0502 *** (0.0161)
lncar			0.1061 *** (0.0107)
lngdp	−0.0453 (0.0472)	0.6343 *** (0.0886)	−0.1343 ** (0.0418)
lnvasi	0.0577 (0.0398)		0.0461 (0.0368)
lnrrd	0.0319 *** (0.0070)	−0.8988 *** (0.2277)	0.1261 *** (0.0109)
cpi	0.0020 ** (0.0009)	0.0065 *** (0.0020)	0.0012 ** (0.0009)
iif	−0.0143 (0.0140)		−0.0683 *** (0.0142)
bus		0.0235 *** (0.0071)	
lnpomd		0.6480 *** (0.1041)	
_cons	3.0029 *** (0.2949)	4.0404 *** (1.1378)	2.7492 *** (0.2673)
Fixed individual effect	YES	YES	YES
Fixed time effect	YES	YES	YES
Sample size	3047	3042	3047
Within R^2	0.0223	0.8522	0.0807

Note: Numbers in brackets are robust standard errors. ***, ** and * represent significance at 1%, 5% and 10% levels, respectively.

Finally, the mediating variable vehicle ownership was added into Equation (1) to test whether there is a mediating effect. The regression results are shown in Table 2, Column (3). According to the regression results, the coefficient of urban sprawl is significantly negative at the 1% level, while the coefficient of vehicle ownership is significantly positive at the 1% level, indicating that vehicle ownership plays an intermediary role between urban sprawl and air pollution. Urban sprawl exacerbates air pollution by increasing vehicle ownership, thus verifying the hypothesis in this paper. In addition, we found that the regression coefficient of urban sprawl changed from positive to negative after introducing the intermediary variable. Thus, after stripping out the intermediate path of urban sprawl's influence on air pollution, the direct path of urban sprawl's influence on air pollution is negative.

From the regression results of control variables, the coefficient of GDP is significantly negative at the level of 5%. The added value of the secondary industry showed a positive promoting effect. The coefficient of consumer price index is significantly positive at the level of 5%. The coefficient of road refreshed degrees is positive at the 1% level. There is a negative relationship between the proportion of fixed assets and air pollution, which may be due to the large amount of fixed assets which are invested in the environmental protection industry, thus playing a role in mitigating air pollution.

5.2. Panel Quantile Regression Analysis

Panel quantile regression is mainly used to explore the relationship between independent variables and dependent variables under different variation ranges of dependent variables. Since the influencing factors of air pollution and car ownership are very complex, in order to further clarify the relationship among urban sprawl, car ownership and air pollution under different levels of air pollution and car ownership, in this paper, the panel quantile regression method was used to conduct the empirical test. As can be seen from the regression results of Equation (2) in Table 3, at the quantile of different levels of vehicle ownership, the coefficient of urban sprawl is still significantly positive; that is, urban sprawl has a positive impact on vehicle ownership, which is consistent with the baseline regression results in Table 2. However, there are significant differences in the coefficient values of each quantile. As the level of vehicle ownership increases from the lower to the higher quantile, the positive promoting effect of urban sprawl on vehicle ownership tends to weaken. This may be because in areas with higher car ownership, the corresponding problems of traffic congestion and parking space shortage are more prominent, and there are more factors restricting people from buying cars, weakening the impact of urban sprawl to a certain extent.

The regression results of Equation (3) in Table 3 show that under different air pollution levels with different quantiles, urban sprawl and vehicle ownership are basically significant, and the coefficient symbols are consistent with the regression results in Table 2 above. The coefficient value of each variable shows that the absolute value of the urban sprawl coefficient is constantly rising, while the coefficient value of car ownership is constantly declining. This indicates that the higher the level of air pollution, the stronger the direct effect of urban sprawl and the weaker the mediating effect of car ownership. This may be because in areas with high levels of air pollution, the government attaches more importance to environmental issues and because environmental control and regulation are increasing.

5.3. Robustness Test

In order to enhance the robustness of the estimation results and to explore whether the difference in city size will have an impact on the correlation between urban sprawl and air pollution, this paper divided the samples into medium-sized cities and non-medium-sized cities for the regression test. The regression results are shown in Table 4. According to the significance and sign of the regression coefficient between urban sprawl and vehicle ownership, it was found that the regression results of both large- and medium-sized cities and non-large- and medium-sized cities are consistent with the previous estimated results in Table 2. Vehicle ownership is the mediating variable of urban sprawl on atmospheric pollution, and vehicle ownership plays a partial mediating role. This suggests that the results of the previous regression are convincing.

In addition, we find that the regression results after sample division are basically consistent, which also indicates that the influence of city size is not obvious.

5.4. Test of Instrumental Variables

The regression results above indicate that urban sprawl affects air pollution, and car ownership plays a mediating role in it. However, considering that the difference in air pollution degree will affect people's economic behavior choice to some extent, it will then affect urban sprawl; in addition, due to the influence of objective reasons, variables will inevitably be omitted in the model. Thus, there is an endogeneity problem, which makes the regression results biased. For the above problems, IV analysis is usually used. In this paper, the urban sprawl index with a lag of one period and the average selling price of commercial housing with a lag of two periods are used as instrumental variables for regression.

There is a certain correlation between urban sprawl in the present period and that in the previous period. At the same time, the urban sprawl in the lag period is not related to the error term of the model. Therefore, the urban sprawl in the lag period satisfies the two conditions of the correlation and exogenicity of instrumental variables and can be used as instrumental variables.

Table 3. Panel quantile regression results.

Model	Explained Variable	Explained Variable	Fixed Effects Regression Model	Regression Results of Each Sub-Site 0.1	0.3	0.5	0.7	0.9
(2)	lncar	sprawl	0.9190 ***	1.2398 ***	1.0091 ***	0.8562 ***	0.7920 ***	0.7120 ***
			(0.0750)	(0.2479)	(0.1258)	(0.0673)	(0.0660)	(0.0891)
(3)	$lnPM_{2.5}$	sprawl	−0.0502 ***	−0.0464	−0.0488 ***	−0.0504 ***	−0.0519 ***	−0.0539 **
			(0.0161)	(0.0295)	(0.0178)	(0.0147)	(0.0175)	(0.0267)
		lncar	0.1061 ***	0.1267 ***	0.1136 ***	0.1055 ***	0.0972 ***	0.0865 ***
			(0.0107)	(0.0171)	(0.0104)	(0.0086)	(0.0102)	(0.0155)

Note: Numbers in brackets are robust standard errors. ***, ** and * represent significance at 1%, 5% and 10% levels, respectively.

Table 4. Regression results of city size by sample.

Table	Medium-Sized Cities			Non-Medium-Sized Cities		
variable	$lnPM_{2.5}$	lncar	$lnPM_{2.5}$	$lnPM_{2.5}$	lncar	$lnPM_{2.5}$
sprawl	0.0461 *	0.8646 ***	−0.0657 **	0.0315 ***	0.9442 ***	−0.0646 ***
	(0.0250)	(0.1476)	(0.0316)	(0.0182)	(0.0899)	(0.0212)
lncar			0.1256 ***			0.1049 ***
			(0.0263)			(0.0122)
_cons	3.1627 ***	1.2566	3.0075 ***	2.9941 ***	4.5773 ***	2.5241 ***
	(0.9790)	(3.1359)	(0.8595)	(0.3015)	(1.1937)	(0.2972)
Control variables	YES	YES	YES	YES	YES	YES
Fixed individual effect	YES	YES	YES	YES	YES	YES
Fixed time effect	YES	YES	YES	YES	YES	YES
Number of city	50	50	50	174	174	174
Sample size	694	695	694	2353	2347	2353
WithinR^2	0.0346	0.8896	0.0952	0.0253	0.8437	0.0826

Note: Numbers in brackets are robust standard errors. ***, ** and * represent significance at 1%, 5% and 10% levels, respectively.

It takes some time for urban sprawl to respond to housing price and for construction to be implemented. That is to say, the current housing price level will affect the urban sprawl in the next period or the next several periods, indicating that there is a correlation between the lagging housing price level and urban sprawl. Moreover, in this model, the current disturbance term is unlikely to affect the lagging house price level. Therefore, we take the average price of commercial housing with two periods lag as the instrumental variable, which can satisfy the correlation and exogenous conditions of the instrumental variable. Considering that the two-period lag of the urban housing price as an instrumental variable will cause the sample to miss two years, this paper adopts the urban housing price from 2001 to 2014 as the instrumental variable of the full sample from 2003 to 2016. In addition, according to Kleibergen–Paap Wald F and Cragg–Donald Wald F statistics, IV passed the validity test.

The specific regression results are shown in Table 5: columns (1) and (2), respectively, represent the regression results taking the lag period of urban sprawl 1 and the lag period of urban housing price level 2 as instrumental variables. It can be seen from the results that after the endogeneity problem is controlled, the results are still consistent with the regression results in Table 2 above, which indicates that the research conclusion of this paper is convincing.

Table 5. Empirical results of instrumental variables.

Explanatory Variables	**Explained Variable (1)**			**Explained Variable (2)**		
	$lnPM_{2.5}$	**lncar**	**$lnPM_{2.5}$**	**$lnPM_{2.5}$**	**lncar**	**$lnPM_{2.5}$**
sprawl	0.0423 *	1.1249 ***	−0.0730 ***	0.0811 **	3.4140 ***	−0.6645 ***
	(0.0240)	(0.0692)	(0.0279)	(0.0415)	(0.1563)	(0.1071)
lncar			0.1142 ***			0.2338 ***
			(0.0114)			(0.0245)
Control variables	YES	YES	YES	YES	YES	YES
Kleibergen–Paap Wald F	228.681	230.202	214.101	283.208	243.927	99.950
Cragg–Donald Wald F	2199.436	2148.513	1657.019	496.688	568.087	103.362
Sample size	2840	2837	2840	3016	3012	3016

Note: Numbers in brackets are robust standard errors. ***, ** and * represent significance at 1%, 5% and 10% levels, respectively.

6. Conclusions

Based on the panel data of 224 prefecture-level and above cities in China from 2003 to 2016, this paper explores the impact of urban sprawl on air pollution and examines the mediating effect of vehicle ownership on the impact of urban sprawl on air pollution. The results show that urban sprawl has a significant positive effect on air pollution and aggravates air pollution. Moreover, car ownership plays a partial mediating role in the positive impact of urban sprawl on air pollution. Finally, through quantile regression, it is further concluded that the higher the level of air pollution, the stronger the direct effect of urban sprawl and the weaker the mediating effect of car ownership.

The above conclusions also show us some policy implications, as follows: first, land use control is important for urban sprawl and in turn, influences air pollution; second, as private car ownership that expands with urban sprawl is proved to be the main factor affecting air pollution, local government may need to invest more into public transportation to reduce private cars. It should be noted that we do not discuss the impact of traffic congestion in this study, although it is an important factor of air pollution emissions. The main reason is that we are unable to obtain the observation data related to congestion, and this part of the work remains for the future, when there are more statistics and sharing of relevant data.

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