Evaluation and analysis of the coordinated development of regional economy in urban agglomerations-Taking the Yangtze River Delta as an example

With the rapid development of urbanization and industrialization, people's living standard has been continuously improved, and the problem of environmental pollution has become increasingly serious. Especially in recent years, fine particulate matter pollution mainly consisting of $PM_{2.5}$ and PM_{10} has appeared frequently in various regions of China. About 100 days in a year in Yangtze River Delta， Pearl River Delta, and Beijing-Tianjin-Hebei region are affected by haze. According to the "GREEN BOOK OF CLIMATECHANGE: ANNUAL REPORT ON ACTIONS TO ADDRESS CLIMATE CHANGE (2016)", air pollution in the Beijing-Tianjin-Hebei region is still relatively serious, with the average number of days which was under the standard during the first three quarters was 39.2% [1]. At the same time, smoggy weather is also a serious threat to people's health level. Studies have shown that for every 5μg/m3 increase, the risk of lung cancer increases by 18%, and for every 10μg/m3 PM_{10} increase, the risk of lung cancer increases by 22%.

Although the causes and governance process of haze itself are complex [3-4], finding out driving factors affecting the smog concentration changes is undoubtedly the key point to the governance process. Therefore, based on the combination of theoretical models and data analysis, this paper takes Nanjing as an example to solve the following questions: (1) What are the main driving factors affecting the variation of $PM_{2.5}$ concentration? Which of these factors play a facilitating role and which of them play a depressive role? (2) What changes should governments, enterprises, and the public make in the management of governance smog?

At present, a large number of scholars have studied the influential factors of $PM_{2.5}$ emissions. According to different implied models and methods, related literature can be roughly divided into three categories:

The first type of the research uses the decomposition model as the main analytical framework, for example, Guan et al. [5] applied structural decomposition analysis to explore the driving factors account for the change of smog emissions in China. The results show that the export is the only final demand to promote the growth of $PM_{2.5}$ Meng et al. [6] used the three-scale input-output model to analyze the impact of domestic and international trade on Beijing $PM_{2.5}$ emissions and revealed that domestic trade played a leading role in the $PM_{2.5}$ emissions in Beijing. Wu et al. [7] analyzed the $PM_{2.5}$ emissions from trade in provinces of China based on a multi-regional input-output model and suggested that the government formulate different policies to control the impact of trade. Xu et al. [8] applied the structural decomposition to air pollutants such as $PM_{2.5}$ and found that although the pollutants still increase in total emissions, the growth rate has slowed down. In addition, the energy intensity has a strong inhibition effect on pollutants. Zhou GuoFu et al. (2017) [9] studied sulfur dioxide, nitrogen oxides, and $PM_{2.5}$ emitted from high-tech manufacturing industries in Tianjin using a structure decomposition technique based on an input-output table to measure the contribution of high-tech manufacturing in pollutant reduction. Lyu et al. [10] applied index decomposition analysis to calculate the absolute and relative contributions of the factors affecting $PM_{2.5}$ changes. The results show that economic growth and energy intensity are the two main driving factors. Emission efficiency, production structure, and population growth contribute little to the overall emissions change. Chen Han and Yu Shiwei [11] factorized the dynamic changes of total $PM_{2.5}$, SO2 and NOx emissions in China. The study found that household income and energy average price are the most important positive and negative driving forces for emissions respectively.

The second type of research uses the econometric models such as EKC curve and STIRPAT model as the analysis framework. Ma Limei and Zhang Xiao [12] used spatial econometrics methods to explore the spatial interaction effects of haze pollution. The results of the research showed that pollution levels are closely related to changes in energy structure and industrial structure. Hao and Liu [13] used the spatial lag model and the spatial error model to study the socio-economic factors affecting the concentration of $PM_{2.5}$, revealing that the motor vehicle and the secondary industry have a significant role in promoting the concentration of $PM_{2.5}$ in the city. Ma et al. [14] analyzed the driving factors of haze based on the spatial EKC model, and suggested that the economic, social, and technical factors of different cities have different effects on $PM_{2.5}$, and different regions are in different EKC curves due to their different economic development status. Liu Huajun and Pei Yanfeng [15] built a spatial Tobit model to test empirically the EKC curve of smog pollution. The study found that the relationship between smog pollution and economic development do not support inverted U-shaped EKC hypothesis. At the same time, economic size and industrial structure and population density have significant positive impacts on smog pollution, and the increase in economic density helps reduce smog pollution. Xu and Lin [16] used the STIRPAT model to analyze the causes of $PM_{2.5}$ in China. The results show that economic growth is the dominant factor in promoting haze growth. In addition, Xu et al. [17] also explored whether there is an EKC assumption between economic growth, the real estate industry, coal consumption, and $PM_{2.5}$ concentration. Shao Shuai et al. [18] used spatial dynamic panel data model to identify the key factors affecting the haze pollution and believed that the promoting factors were not effectively suppressed and the factors aimed to decrease did not come into effect, which was the root cause of frequent haze pollution in China.

The third type of research uses the rest of the models except the first and second type's models as the analytical framework. Jiang et al. [19] used the structural equation model to quantify the relative contributions of different social and economic factors to $PM_{2.5}$. The results showed that industrial activities contributed the most to $PM_{2.5}$ pollution, and the urban scale and residents' activities also had a significant impact on $PM_{2.5}$ pollution. Wu et al. [20] studied the determinants of haze in China based on the random effects model. The study found that $PM_{2.5}$ was significantly related to the proportion of industry, number of vehicles, and household gas consumption. Li et al. [21] studied $PM_{2.5}$ influence factors using the fish bone map method. In addition, there are a number of documents that provide targeted analysis of $PM_{2.5}$ sources, mainly including emission inventory methods [22-23], diffusion model methods [24-25], and receptor-oriented model [26-27].

Although the above studies have drawn rich conclusions, some limitations have also been exposed, mainly due to the timeliness of the data brought by the input-output table and the drawbacks that Vaninsky points out in IDA. In this paper, under the current situation of frequent haze problems, combined with the domestic and abroad researches' present situation of haze, from the socio-economic point of view, try to expose the driving factors affecting $PM_{2.5}$ emissions. The article will use the GDIM (Generalized Divisia Index Method, Vaninsky, 2014) [28] to factorize the $PM_{2.5}$ in Nanjing, explore the contribution of different factors to the concentration of $PM_{2.5}$, and propose corresponding countermeasures based on the calculation results. It hopes that in the current state of frequent haze, potential driving factors and countermeasures will be found for Nanjing to improve local environmental quality and promote sustainable economic development.

1 Data selection and description

According to the related research of PM2.5 and air pollutants domestic and abroad, in terms of this paper, the selection of PM2.5 influencing factors and their measurement indicators are described below.

（1）Energy consumption. The use of large amounts of non-clean energy, especially oil and coal, is a key factor causing serious haze problems [10; 12; 29], while China is still in the development stage, and its energy consumption structure is dominated by coal. Therefore, this article considers integrated energy consumption as one of the influencing factors.

（2）Economic growth. In fact, due to the rapid economic development, energy consumption has been correspondingly growing rapidly. From a causal perspective, economic growth is the root cause, and the growth of energy consumption is one of the manifestations. Therefore, this paper will use Gross Domestic Product(GRP) as a parameter to measure economic growth.

（3）Total population. As population is a driving factor, its impact on haze can usually be divided into positive aspect and negative aspect [30-31], and it always shows up in the literature in the form of population density [15; 21]. Considering the small scope of the study in this paper, only taking Nanjing as an example, there is no difference in administrative area between provinces [18], and it is convenient for subsequent model calculations. This paper directly selects the resident population as a measure.

（4）Industrialization and industrial structure. As we all know, China is at an accelerated stage of industrialization. The concentration of industrial economy is closely related with the severity of smog pollution [32]. At present, China's growth pattern is still dominated by extensive mode of growth with high energy consumption and low efficiency. In addition, the success of China's real estate industry has also driven the operating time of heavy industry industries such as the construction industry and steel industry [33], further aggravating haze pollution. Therefore, this paper will take industrialization and industrial structure as influential factors and uses the second industry's GDP to measure the degree of industrialization and the proportion of the second industry's GDP to the region GDP to measure the industrial structure.

（5）Foreign direct investment (FDI). The relationship between FDI and smog can be mainly divided into two perspectives. One is that FDI has intensified the negative impact of smog on the environment. It is called Pollution Haven Hypothesis [34-35], and the other thinks that FDI promotes environmental improvement positively. The role is called Pollution Halo Hypothesis [36-37]. In view of the fact that the effect of FDI on smog has not been unified, this article believes that this factor is necessary for research and uses the amount of foreign capital actually used as its measurement method.

（6）Transportation. During the transportation process, a large amount of exhaust gas will be generated. The main components of the exhaust gas are solid suspended particulates, CO, NOx, SOx and other substances, all of which promote the haze pollution. At present, some scholars have pointed out that the impact of automobile traffic patterns and public transportation modes on smog is not exactly the same, and only the mode of automobile traffic has brought a positive spillover effect on haze pollution [38]. Therefore, this paper only considers the mode of automobile traffic and uses the number of civil vehicles as a measurement index.

（7）According to the demand of the GDIM model, there will be a series of additional indicators in this paper. These indicators are all relative indicators of the above indicators (except for the industrial structure). Taking energy consumption as an example, the meaning of the corresponding relative indicators represents the $PM_{2.5}$ concentration related to the unit energy consumption, the remaining relative indicators are similar.

Considering the availability of $PM_{2.5}$ concentration data, the data covered in this paper is composed of the panel data of Nanjing from 2013 to 2016. Among them, the $PM_{2.5}$ concentration data comes from China Statistical Yearbook (2014-2017), and the rest metric data comes from Statistical Yearbook of Nanjing (2014-2017) to ensure the accuracy and authority of the data.

2 Model establishment

Decomposition analysis has been widely used in the study of exploring driving factors. At present, there are mainly two methods that are widely used, namely Structural Decomposition Analysis (SDA) and Index Decomposition Analysis (IDA). SDA is a method based on the input-output table to decompose driving factors. Since input-output tables can reflect the entire economic situation of a country or region, the scope of application of this method is broad [39]. At the same time, this also exposes the shortcomings of this method, because the input-output table is not compiled year by year. For example, China's recent input-output table is 2012, which may cause data timeliness. In contrast, IDA has lower requirements on data [40]. LMDI (Logarithmic Mean Divisia Index) method proposed by Ang [41] overcomes the defects of IDA's residuals and zeros in history, and it also has certain flexibility in use. Thus, IDA has been favored by more scholars.

However, according to the study of Vaninsky [28], all current IDA methods, including LMDI, still have some deficiencies, which are mainly reflected in two aspects: (1) few quantitative indicators, most models only contain single quantitative indicator. (2) There is a possibility that decomposition models are similar but decomposition results are different. In order to avoid the above two issues, Vaninsky [28] proposed a new factor decomposition technique, namely the generalized Divisia index model. Since GDIM can simultaneously reflect the changes in quantitative indicators and ratio indicators, a more comprehensive and accurate factor contribution of the numerical results can provide a more comprehensive and rational explanation of the analysis results. Therefore, this paper will consider GDIM as the main factor decomposition method.

Based on the above-mentioned influential factors of the $PM_{2.5}$ concentration and the GDIM model proposed by Vaninsky, the $PM_{2.5}$ concentration is decomposed into the following sections (the definitions of the relevant variables are listed in Table 1):

$$\begin{aligned} PM &= X_1X_2 = X_3X_4 = X_5X_6 \\ &= X_7X_8 = X_9X_{10} = X_{11}X_{12} \\ X_{13} &= X_5/X_1 \end{aligned} \tag{1}$$

In order to facilitate the application of GDIM, this paper rewrites formula (1) as follows:

$$PM = X_1X_2,\ X_1X_2 - X_3X_4 = 0$$
$$X_5X_6 - X_7X_8 = 0,\ X_9X_{10} - X_{11}X_{12} = 0 \qquad (2)$$
$$X_1X_2 - X_9X_{10} = 0,\ X_5 - X_1X_{13} = 0$$

Based on this, use the first-order partial derivative of equation (2) to obtain the gradient ∇PM of the function $PM = X_1X_2$ and the Jacobian matrix $\mathbf{\Phi}_X$.

$$\nabla PM = \begin{pmatrix} X_2 & X_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}^T$$

$$\mathbf{\Phi}_X = \begin{pmatrix} X_2 & X_1 & -X_4 & -X_3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & X_6 & X_5 & -X_8 & -X_7 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & X_{10} & X_9 & -X_{12} & -X_{11} & 0 \\ X_2 & X_1 & 0 & 0 & 0 & 0 & 0 & 0 & -X_{10} & -X_9 & 0 & 0 & 0 \\ -X_{13} & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -X_1 \end{pmatrix}^T$$

This matrix contains the effect on the $PM_{2.5}$ concentration when a small change occurs in each factor, that is, the contribution of each factor to the $PM_{2.5}$ concentration change. At the same time, it is not difficult to find out from formula (2) that each factor is related and any factor can be represented by other multiple factors, that is, the conditions of using GDIM model are satisfied. Therefore, the final factorization expression for $PM_{2.5}$ concentration changes is as follows:

$$\Delta PM\left[X \mid \mathbf{\Phi}\right] = \int_L \nabla PM^T \left(\mathbf{I} - \mathbf{\Phi}_X \mathbf{\Phi}_X^{+}\right) dX$$

X on behalf of each of the drivers in $X_1, X_2, \cdots, X_{13}$, $\Delta PM\left[X \mid \mathbf{\Phi}\right]$ represents the contribution rate of the current driving factor to the change of $PM_{2.5}$ concentration, which is the decomposition result to be calculated in this paper. L represents the time span, and $\mathbf{\Phi}_X^{+}$ represents the generalized inverse matrix of $\mathbf{\Phi}_X$. In the premise that each column vector of $\mathbf{\Phi}_X$ is linearly independent, $\mathbf{\Phi}_X^{+}$ can be expressed as $\mathbf{\Phi}_X^{+} = \left(\mathbf{\Phi}_X^T \mathbf{\Phi}_X\right)^{-1} \mathbf{\Phi}_X^T$, and $\mathbf{I}$ represents the identity matrix.

3 Analysis of $PM_{2.5}$ emission driving factors

3.1 Statistics Description

In 2012, China revised and released of the Ambient Air Quality Standard (GB 3095-2012), adding $PM_{2.5}$ concentration limit. In 2013, the annual average concentration of $PM_{2.5}$ in Nanjing was 78μg/m3, exceeding the national secondary limit of 122.86%. In 2016, the annual average concentration of $PM_{2.5}$ in Nanjing improved to 48μg/m3, exceeding the national secondary limit of 37.14%. Although the $PM_{2.5}$ concentration in the area has dropped by 38.46% in the past 4 years, it has not reached the national limit standard. Air pollution caused by smog still poses a potential threat to humans. Figure 1 describes the trend of the changes in the above absolute quantitative factors (take 2013 as the base year) in detail from 2013 to 2016. Considering the different units of measurement of each factor, this article will convert them into percentage forms for convenient comparison. As can be seen from Figure 1, the number of the possession of civil vehicles, GDP, total secondary industry's GDP and total energy consumption have risen or slowly risen. Compared with 2013, the four figures in 2016 increased by 32.76%, 31.09%, 19.32%, and 8.67% respectively, which shows that Nanjing is in the stage of continuous economic development and still needs to consume more energy. At the same time, the increase in the number of the possession of civil vehicles has also reflected the improvement of people's living standards. The total population has remained basically unvaried for four years, only increasing by 1%. The secondary industry's share of GDP has been declining year by year. By 2016, it was only initial's 91.02%. It can be inferred that the industrial structure of Nanjing is gradually diversifying. Of all the factors, only FDI has reached a turning point (in 2014). The factor dropped first and then rose. However, it did not return to the state of 2013 until 2016, and the general declined by 13.74%. It can be inferred from looking up the policy papers of Nanjing government for foreign merchants that in 2013, the government's newly issued foreign investment procedures may make some foreign companies unwilling to adapt and choose to withdraw. However, as time goes by, foreign merchants can gradually adapt to the new environment. So, after 2014, FDI slowly picked up.

3.2 Factor decomposition results and analysis

3.2.1 Factor decomposition results

This paper uses Python language to calculate and solve GDIM, and then it obtains the contribution rate of each factor to the changes of $PM_{2.5}$ concentration, finding the average value. The result is shown in Figure 2.

From Figure 2, we can see that each factor has a different degree of contribution to the change of $PM_{2.5}$ concentration, but in general it can be divided into two categories: positive influence (promote the increasing of $PM_{2.5}$ concentration) and negative influence (inhibit the increasing of $PM_{2.5}$ concentration). In order to clearly illustrate the two different types of influence, the factors are sorted according to the influence direction and the degree of influence (use absolute values to sort for easy understanding). Results are shown in Table 2.

From Table 2, we can see that the number of the possession of civil vehicles（C）and the regional GDP（G）play a significant role in promoting the change of $PM_{2.5}$ concentration. The contribution rates are 14.38% and 10.48% respectively, which are beyond the $PM_{2.5}$ concentration（PM/S）related to the unit of the secondary industry's GDP 417.27% and 276.98%. Relatively, the $PM_{2.5}$ concentration（PM/G）associated with unit of regional GDP and the $PM_{2.5}$concentration associated with unit of civil vehicles have a strong inhibitory effect on the $PM_{2.5}$ concentration, and their contribution rates are as high as 43.69% and 38.27% respectively. In addition, the $PM_{2.5}$ concentration（PM/S）related to the unit of the secondary industry's GDP and the industrial structure （S/G）contribute to the change of $PM_{2.5}$ concentration, which are 2.78%,2.75% and 1.92% respectively. The $PM_{2.5}$ concentration（PM/P）related to per population, foreign direct investment（F）, the $PM_{2.5}$ concentration（PM/F）related to the unit of foreign direct investment, and the $PM_{2.5}$ concentration（PM/E）related to the unit of energy consumption have a mitigation effect of 24.75%, 16.17%, 7.94%, and 2.40%, respectively, on changes in $PM_{2.5}$ concentrations. The resident population（P）and energy consumption（E）played a weak promotion role for the change of $PM_{2.5}$ concentration, which was 0.51% and 0.37% respectively.

Except the average contribution rate, in order to explore the specific performance of various factors in different years, this paper considers that the contribution rate of each factor in different years also needs to be compared. Numerical results are shown in Table 3.

In order to compare the changes in the contribution of each factor over the three years more clearly, the above results are plotted as shown in Figure 3.

3.2.2 Result analysis

It is not difficult to find that the performance of each factor is approximately the same as the actual situation. The performance of each factor is discussed and analyzed below.

（1）Transportation. Transportation plays a significant role in the entire process of $PM_{2.5}$ concentration change. It can be seen that the emissions emitted by vehicles during transportation can indeed aggravate the pollution of the atmospheric environment. Common manifestations are the emission of black smoke and blue smoke. It shows that in the current traffic environment, the phenomenon of incomplete combustion of fuel and so on exists in most vehicles. Combining with Figure 1, it can be concluded that the possession of civil vehicles （C）will continue to increase in the future, and it will inevitably have a greater impact on atmospheric environmental pollution, which needs to be given attention. On the other hand, the concentration of $PM_{2.5}$（PM/C）associated with the unit of civil vehicles shows a significant inhibitory effect. In fact, this inhibitory effect is fully reflected in the type of energy used by vehicles, such as electric cars, fuel cell vehicles, etc. These vehicles can achieve zero emissions or near zero emissions, but they are not widely used yet. So, it has great potential.

（2）Economic growth. The regional GDP（G）is the second largest driving factors which promotes the increase of $PM_{2.5}$. The main reason is that the regional GDP of Nanjing is mainly dominated by the secondary and tertiary industries. The wholesale industry and transportation in the tertiary industry are closely related. The real estate industry can also drive the development of the construction industry in the secondary industry. Therefore, the greater the vibrancy of these industries, the greater the economic benefits generated, and the more serious damage to the atmosphere. But this situation can be changed, considering that the $PM_{2.5}$ concentration (PM / G) associated with the unit of region GDP can effectively alleviate the $PM_{2.5}$ concentration. The information it reveals can be summarized in two points. First, industries that have no direct relationship with changes in $PM_{2.5}$ concentrations should accelerate the pace of development. Second, in the premise that if the industries linked to the changes of $PM_{2.5}$ concentration remain under the current impact on $PM_{2.5}$, increase their own growth rate to the regional GDP, it is also a way to reduce the concentration of $PM_{2.5}$.

(3) Industrialization and industrial structure. The secondary industry's GDP (S), the $PM_{2.5}$ concentration (PM / S) related to the unit of the secondary industry's GDP and the ratio (S / G) of the secondary industry's GDP to the total GDP all promote to the change of $PM_{2.5}$ concentration. It shows that during the process of industrialization, Nanjing still focuses on extensive industrial development model. Figure 1 shows that the industrial structure of Nanjing has gradually improved, but from the factor decomposition results, it still does not reach the ideal state. Long-term industry activities will continue to harm the atmospheric environment.

(4) Total population. The total population changes little in 4 years. Therefore, the resident population (P) has only a slight positive effect on the change of $PM_{2.5}$ concentration. The likely reason is that the growth of population leads to an increase in the demand for housing and vehicles. In densely populated areas, it is easier to form traffic jams in the morning and evening rush hours, resulting in black smoke, blue smoke and another automobile exhaust. The mitigation effect of the $PM_{2.5}$ concentration (PM / P) related to per population is mainly due to the fact that people themselves have strong subjective initiative, responding to the local government's call, choosing public transport to travel, and increasing the utilization of resource.

(5) Energy consumption. According to factor decomposition results, energy consumption (E) also promotes $PM_{2.5}$ concentration. This is mainly due to the fact that coal, oil and other fuels still occupy a large proportion of the total energy in Nanjing. In the process of energy using, there exists direct emission of waste gas without green treatment, which in turn increases the occurrence of hazy weather. The $PM_{2.5}$ concentration (PM / E) related to the unit of energy consumption can alleviate the haze phenomenon. This factor reveals that when the energy source is fully utilized and no exhaust gas is produced, it will have a certain inhibitory effect on the haze phenomenon, that is, the renewable or green energy can be used in the future to replace traditional fossil energy, increasing energy efficiency and reducing pollutant emissions at the same time.

(6) Foreign direct investment. The direct foreign investment (F) and the concentration of $PM_{2.5}$ (PM / F) associated with unit foreign direct investment all inhibit the change of $PM_{2.5}$ concentration. The " Pollution Haven Hypothesis" was not established in Nanjing. The role of the two can be summarized as the addition of FDI is conducive to the improvement of Nanjing overall income level which means that more funds will be invested to environmental protection. In addition, the entry of foreign companies may bring home country's environment-friendly technologies and products, and it will also have certain benefits for local environmental protection.

In addition, the analysis of Figure 3 shows that the contribution of each factor to the change of $PM_{2.5}$ concentration in different years can be roughly divided into four categories:

(1) Decrease year by year. Which shows as gradually decrease year by year among the contribution rate of each factor are region GDP (G) and the number of the possession of the civil vehicles (C) . This phenomenon indicates that the relevant departments in Nanjing have realized to transit from rapid economic growth to slow economic growth and gradually control the congestion problem in transportation.

(2) The contribution rate in 2015 is high. The factors with high contribution rate in 2015 included the $PM_{2.5}$ concentration (PM / G) related to the unit region GDP, the $PM_{2.5}$ concentration of unit of population, and the $PM_{2.5}$ concentration of unit civil vehicles. By comparing the changes in $PM_{2.5}$ concentration, it can be seen that the reason accounts for this phenomenon might be that the variation of $PM_{2.5}$ concentration, which is $-17 \mu g / m^3$, is relatively large from 2014 to 2015. Therefore, the factor contribution rate also increases correspondingly, and the contribution rate of factors that produce negative effects changes much more than the factors that produce positive effects.

(3) The contribution rate is basically unchanged. The contribution rate of the resident population (P) , the $PM_{2.5}$ concentration (PM / S) related to the secondary industry's GDP, energy consumption (E) , the $PM_{2.5}$ concentration (PM / E) related to the unit of energy consumption, and the ratio (S / G) of the secondary industry's GDP to the total GDP to the $PM_{2.5}$ contribution in the three-year remained basically unchanged. One of the main features of the above factors is that the annual contribution rate is relatively low and may not dominate in the contribution to the entire $PM_{2.5}$ concentration change, so the contribution rate has only changed slightly.

(4) The direction of contribution has changed. The factors that cause this phenomenon are foreign direct investment (F) and the concentration of $PM_{2.5}$ (PM / F) associated with unit foreign direct investment. The contribution rate

of foreign direct investment （ F ） between 2013 and 2014 is negative. The contribution rate of the latter two years is positive, however, the contribution rate of the concentration of $PM_{2.5}$ （ PM / F ） associated with unit foreign direct investment is the opposite. Combined with Figure 1, the amount of FDI has decreased significantly from 2013 to 2014. The company may not have enough funds to adopt green product management, but foreign companies themselves environment-friendly technologies will also suppress the concentration of $PM_{2.5}$. effect. In the following two years, with the gradual increase of FDI, Nanjing has a weak "Pollution Haven effect." Since the region is still under the lead of "Pollution Halo effect", the promotion effect is not yet obvious, but it still needs attention.

4 Conclusions and suggestions

4.1 Conclusions

In order to avoid the defects in the traditional IDA, this paper innovatively uses the generalized Divisia index decomposition method to calculate the driving factors of $PM_{2.5}$ in Nanjing, and to enrich the relevant theoretical models of current $PM_{2.5}$ emission driving factors. Based on the above analysis, the basic conclusions of this paper are as follows:

（1）Take 2013 as the base period, $PM_{2.5}$ concentration decreased by 30μg/m3 in 2016. According to the factor decomposition results of the GDIM model, the number of the possession of the civil vehicles（ C ）, region GDP（ G ）, the $PM_{2.5}$ concentration（ PM / S ）related to the secondary industry's GDP, the secondary industry's GDP（ S ）, the industrial structure（ S / G ）, the resident population（ P ）and energy consumption（ E ） have positive impacts on the change of $PM_{2.5}$ concentration were 14.38%,10.49%,2.78%,2.75%,1.92%,0.51% and 0.37% respectively； That have negative impacts on the change of $PM_{2.5}$concentration are the $PM_{2.5}$concentration（ PM / G ）associated with the unit of region GDP, the concentration of $PM_{2.5}$（ PM / C ）associated with the unit of civil vehicles, the $PM_{2.5}$ concentration （ PM / P ）related to per population, foreign direct investment（ F ）, the $PM_{2.5}$ concentration（ PM / F ）related to the unit of foreign direct investment, and the $PM_{2.5}$ concentration（ PM / E ）related to the unit of energy consumption. They average contribution to the change of $PM_{2.5}$ concentration is 43.69%,38.27%,24.75%,16.17%,7.94% and 2.40% respectively。

（2）The number of the possession of civil vehicles（ C ） and the region GDP（ G ）have become the biggest driving factors which promotes the increase of $PM_{2.5}$ concentrations. This shows that the traditional extensive mode of growth and the large amount of exhaust emissions from transportation do contribute a lot to promoting $PM_{2.5}$, although the number of the possession of the civil vehicles（ C ）and region GDP（ G ）increased from 2013 to 2016, but its growth rate has a tendency to decrease, and at the same time, according to the results of factor decomposition, the contribution rate of both is gradually decreasing. On the other hand, the $PM_{2.5}$ concentration （ PM / G ） related to the unit region GDP; and the $PM_{2.5}$ concentration（ PM / C ）associated with the unit of civil vehicles have become the biggest driving factor to inhibit the increase of $PM_{2.5}$ concentration. The functions of the two factors' inhibition were strong during the three years, and they were most useful in 2015. This further demonstrated that it is both potential and necessary to begin to manage haze problems in terms of transportation and economic growth. At present, the source of economic growth is mainly the secondary industry. In the future, more emphasis should be placed on the development of industries that are less relevant to $PM_{2.5}$ emissions, which will make the economic growth more diversified. At the same time, we can also use public transportation to travel or conveyance applying clean energy.

（3）Foreign direct investment（ F ）and the concentration of $PM_{2.5}$（ PM / F ） associated with unit foreign direct investment show different directions of contribution at different stages. From 2013 to 2014, foreign direct investment（ F ） was negatively impacted, with a contribution rate of 4.70%. During this period, the concentration of $PM_{2.5}$（ PM / F ） associated with unit foreign direct investment showed a positive effect with a contribution rate of 3.48%. Due to the sudden drop in FDI in 2014, companies may not have enough funds to adopt green product management, but foreign companies' environment-friendly technologies will play a certain role in inhibiting $PM_{2.5}$ concentrations. From 2014 to 2015 and from 2015 to 2016, foreign direct investment（ F ）has turned into a positive effect, and it may increase year by year, but the concentration of $PM_{2.5}$（ PM / F ）associated with unit foreign direct investment changes into a negative effect, and there are possibilities of decreasing annually. All these suggest that Nanjing is showing a faint "Pollution Haven effect." Since the region is still under the leadership of the "Pollution Halo effect," the promotion effect is not obvious and needs attention.

4.2 Suggestions

Based on the above calculation results and analysis contents, in order to improve the environmental quality of Nanjing and promote the sustainable development of the local economy in the current state of frequent haze, this paper proposes the following suggestions:

(1) Establish a green transportation system as soon as possible. On the one hand, Nanjing should further alleviate the growth rate of the possession of civilian vehicles, improve the public transportation mechanism, and appeal the public to choose more often transportation such as buses and subways. On the other hand, Nanjing should also promote the development of green vehicles, reduce transportation's dependence on fossil fuels, and strive to achieve or approach the aim of zero emissions.

(2) Accelerate the transformation of economic development mode. As China is in the stage of industrialization and urbanization, Nanjing responds to the national call——from 2013 to 2016, the continuous increase in region GDP is undoubtedly worthy of recognition. However, the problem of haze it brings could not be underestimated. Thus, under the circumstances of maintaining a certain speed of economic growth, it is crucial to modify the industrial structure, transfer the development mode centered on the secondary industry and reduce the proportion of industry in the economy.

(3) The energy structure still needs to be adjusted. The policy of using clean energy has been proposed for many years and has achieved certain effects. However, in most cases, the energy structure is still dominated by coal and it is difficult to transform in a short time. Therefore, under the circumstances of accelerating the development of clean energy and renewable energy, the harmless treatment of coal and the improvement of coal utilization are also necessary.