Decoupling relationship between economic growth and PM$_{2.5}$ emissions in the transportation sector in China: regional differences and influencing factors

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Abstract

PM$_{2.5}$ emissions from the transportation sector are a source of haze pollution in China, to which, however, less attention is paid by society. The decoupling relationships between PM$_{2.5}$ emissions and economic growth from the transportation sector in the eastern, central, and western regions of China from 2010 to 2017 are analyzed by using the Tapio decoupling model. On this basis, in the transportation sector, socioeconomic factors influencing PM$_{2.5}$ emissions and effective means of controlling PM$_{2.5}$ emissions are studied by using a logarithmic mean Divisia index model. The results indicate that: (a) in China’s transportation sector, the decoupling relationships of the two aspects in the eastern, central, and western regions show an N-shaped trend, that is, the rate of change in PM$_{2.5}$ emissions from the transportation sector gradually exceeds that of economic development. The strong decoupling changes into an expansive coupling in the eastern and central regions, while the strong decoupling becomes an expansive negative decoupling in the western region. (b) Economic growth and population growth mainly contribute to the increase of PM$_{2.5}$ emissions. Improvements of the energy structure and a decrease in transport intensity are the main factors driving a reduction in PM$_{2.5}$ emissions. (c) Due to regional differences in the ‘rebound effect’ and ‘technological effect’, technological progress has increased PM$_{2.5}$ emissions from the transportation sector in the central region, while reduced such emissions in the eastern and western regions. This research provides targeted policy reference for regional governance of PM$_{2.5}$ emissions from the transportation sector.

1. Introduction

PM$_{2.5}$ (generally refers to particulate matter with an aerodynamic equivalent diameter less than or equal to 2.5 μms), as a main component of haze, has seriously affected people’s productivity and lives [1–3]. To control PM$_{2.5}$ pollution, the Chinese Government promulgated an Action Plan for Air Pollution Prevention and Control in 2013 [4]. Benefiting from the regulation of the policy, PM$_{2.5}$ emissions from the industry, power, and household sectors were separately decreased by 40%, 31%, and 28% from 2013 to 2017 [5]. Meanwhile, PM$_{2.5}$ emissions from the transportation sector were increased by 3%, and its proportion of the total societal emissions was increased from 4.6% in 2013 to 7.1% in 2017. Compared with other sectors, emissions from transportation increase, therefore, PM$_{2.5}$ emissions from the transportation sector have hindered the emission-reduction process insofar as it relates to PM$_{2.5}$ across the whole of society. More significantly, the transportation sector has become the primary source of PM$_{2.5}$ emissions in some cities. For example, in 2017, PM$_{2.5}$ emissions from the transportation sector in cities, such as Shenzhen, Beijing, Jinan, Shanghai, Hangzhou, and Guangzhou accounted for 52.1%, 45%, 32.6%, 29.2%, 28%, and 21.7% of the total emissions in these cities, respectively [6]. In the future, if no other intervention is taken, with the continuous improvement of people’s living standards and the
constant increase of car ownership, the pressure on
controlling PM\textsubscript{2.5} emissions from the transportation
sector will be mounting.

Due to the vast areal extent of China, there
are regional imbalances in transportation services,
vehicle ownership and transportation infrastructure
in the east, central, and western regions, as well as
different emission reduction potentials and environ-
mental supervision efforts, which are prone to
problems of regional environmental imbalances [7].
Historical data indicate that economic development,
transportation energy consumption, and pollution
emissions tend to be high in the east and low in the
west [8]. Among them, in the transportation sector,
PM\textsubscript{2.5} emissions in eastern China were about 48% of
total emissions (central and western China account-
ted for about 31% and 21% thereof). To achieve the
win-win goal of economic development and haze
control, it is necessary to evaluate the ability of
the regional transportation sector to grow without
increasing PM\textsubscript{2.5} emissions (i.e., the decoupling effect)
[9] and its related drivers at the regional level from the
perspective of the transportation sector.

The present study is designed to answer the fol-
lowing questions: in the transportation sector, what
is the ability of eastern, central and western China
to grow economically without increasing PM\textsubscript{2.5} emis-
sions? What are the socioeconomic factors affecting
PM\textsubscript{2.5} emissions and their influencing mechanisms?
To answer these questions, the Tapio decoupling
model [9] are combined with the logarithmic mean
Divisia index (LMDI) model [10] to reveal the
decoupling relationships between PM\textsubscript{2.5} emissions
from the transportation sector and economic growth
in the eastern, central, and western regions of China.
Furthermore, factors influencing the decoupling rela-
tionship, including the energy structure, technolo-
gical progress, transport intensity, economic growth,
and population are analyzed. This study has impor-
tant practical significance for appropriately setting
the goal of PM\textsubscript{2.5} emission reductions from the transpor-
tation sector. The results provide an intuitive perspec-
tive for promoting the coordinated growth of PM\textsubscript{2.5}
emission reductions and the regional economy.

The contributions of this research are mainly
reflected in the following two aspects: (a) Different
from previous studies that use PM\textsubscript{2.5} concentration as
the monitoring indicator [11, 12], this research is
designed so as to adopt data related to PM\textsubscript{2.5} emis-
sions. (b) Previous studies focus on CO\textsubscript{2} emissions
[7, 8, 13], energy consumption [14, 15], and chemical
mechanisms of PM\textsubscript{2.5} pollution [3] from the transpor-
tation sector. Unlike these, the present research
attempts to ascertain differences in PM\textsubscript{2.5} emissions
from a regional perspective and reveal the underly-
ing mechanisms of any socioeconomic impacts, so as
to fill the research gap in the understanding of air
pollution in the transportation sector. It should be
noted: although the PM\textsubscript{2.5} concentration data show
advantages such as intuitiveness and being easy to be
monitored at the city level, they are greatly affected
by factors such as meteorology and geography [16].
The use of PM\textsubscript{2.5} emission data can avoid errors of the
aforementioned factors in socio-economic research.
In this case, we focus on primary PM\textsubscript{2.5} emissions,
which account for a large portion of PM\textsubscript{2.5} pollution
in China [17]. The main source of primary PM\textsubscript{2.5}
emissions is fossil fuel consumption [18], which is
directly affected by socioeconomic factors. Second-
ary PM\textsubscript{2.5} emissions come from the oxidation of other
air pollutants and contribute to the total amount of
PM\textsubscript{2.5}, but the formation of secondary PM\textsubscript{2.5} emis-
sions shows complex chemical changes and has cer-
tain uncertainties [19]. Therefore, we do not further
consider secondary PM\textsubscript{2.5} emissions.

2. Literature review

Haze pollution, as a natural phenomenon, is one of
the most serious environmental problems in China
[20], but its causes lie in socioeconomic activit-
ies [21]. Some studies show that haze pollution is
related to economic growth [22, 23]. According to
the theory behind the environmental Kuznets curve,
economic growth usually causes an increase in pol-
lution emissions, however after implementing effect-
ive mitigation policies, higher economic growth will
be accompanied by lower pollution emissions, which
can be regarded as a decoupling [24]. The decou-
pling implies that economic growth is divorced from
environmental pollution, which allows analysis of the
dilemma at the nexus between them [25]. Decoupl-
ing analysis can elucidate the relationship between
research objects through elasticity and shows simple
calculation and intuitive results [26]. It is considered
a good choice [27] when studying the relationship
between economic development and pollution emis-
sions, which has been widely used in the research of
energy [14, 28] and carbon emissions [7, 8, 13, 29].
However, at present, the PM\textsubscript{2.5} decoupling has been
mostly studied at the national [25, 30] or regional
level [11, 31], while is less often used at the sectoral
level. Although Fang et al. [24] assessed the decoupling
relationship between PM\textsubscript{2.5} emissions from industry
and industrial growth in China, there is no research
on PM\textsubscript{2.5} emissions from the transportation sector.

There are four key methods used to evaluate
factors influencing PM\textsubscript{2.5} emissions: the Stochastic
Impacts by Regression on Population, Affluence, and
Technology model (STIRPAT), Production Decom-
position Analysis (PDA), Structural Decomposition
Analysis (SDA), and the logarithmic mean Divisia
index (LMDI) method (table 1).

Compared with other methods, although the
LMDI model, as a branch of index decomposi-
tion analysis, cannot decompose multiple influen-
cing factors [38], its decomposition factors are easy
to explain, thus making the model more applicable [26]. Some scholars have employed the LMDI model to estimate the effects of drivers on PM\(_{2.5}\) pollution, such as the emission coefficient, energy structure, economic output, energy efficiency, and population [21, 31]. In particular, Zhang et al [11] found that PM\(_{2.5}\) emission intensity and investment efficiency accelerate the regional decoupling. Dong et al [22] proposed that the synergistic effect of carbon emissions is the main factor promoting reductions in PM\(_{2.5}\) emissions. A few scholars have analyzed factors influencing for PM\(_{2.5}\) emissions from the industry [24] and freight [37] of China and considered that improving energy efficiency will promote emission reductions. Most studies suggest that the LMDI model can be used to reveal the mechanisms of influence, and extent of, key socioeconomic factors and their effects on changes in PM\(_{2.5}\) emissions. Therefore, after comparing the advantages and disadvantages of the four models, the LMDI model is chosen for the analysis of those factors affecting PM\(_{2.5}\) emissions from the transportation sector in the eastern, central, and western regions of China.

Existing studies mainly focus on the whole-of-society, industry, or other sources, and few scholars have studied PM\(_{2.5}\) emissions from the transportation sector of China. To explore regional differences in PM\(_{2.5}\) emissions from the transportation sector, the decoupling state between PM\(_{2.5}\) emissions from the transportation sector and economic growth is revealed based on decoupling theory. The internal drivers of PM\(_{2.5}\) emissions from the transportation sector are researched by combining such data with an LMDI model. The research provides some new insights into high-quality development of the transportation sector in each region.

### 3. Models and data sources

#### 3.1. Tapio decoupling model

The decoupling model is introduced to determine the degree of dependence of PM\(_{2.5}\) emissions from the transportation sector on economic growth. The decoupling model includes the Organization for Economic Cooperation and Development index-based decoupling method, Velma decoupling index method, and Tapio elastic coefficient method [14, 39]. The Tapio model enables further subdivision of the decoupling state, with more accurate results. Therefore, the Tapio model is selected to study the decoupling state between PM\(_{2.5}\) emissions from the transportation sector and economic output. The governing formula is as follows:

\[
\rho = \frac{(PM_t - PM_0) / PM_0}{(TA_t - TA_0) / TA_0} = \frac{\Delta PM / PM_0}{\Delta TA / TA_0}
\]

where, PM\(_t\) and PM\(_0\) represent the PM\(_{2.5}\) emissions at time \(t\) and the base period \(t_0\), respectively; TA\(_t\) and TA\(_0\) indicate the added values in the transportation sector at times \(t\) and \(t_0\), respectively.

Tapio [9] introduced an elastic coefficient into the decoupling model and defined that the increase and

| Method | Advantages | Disadvantages | Reference | Research factors |
|--------|------------|---------------|-----------|------------------|
| STIRPAT | Possess IPAT theoretical support; can arbitrarily expand the number of indicators. | The selection of factors is subjective and has the influence of random errors. | Xu and Lin [32]; Zou and Shi [12] | Economic growth, Urbanization & Population, Industrial agglomeration |
| PDA | Can analyze micro-factors related to ‘efficiency’. | Efficiency estimation affects the accuracy of results; lack of discussion on structural components (energy structure, etc.). | Lu et al [2]; Xu et al [33]; Wang et al [34] | Output efficiency & Technological progress, Efficiency improvement & Technological progress |
| SDA | Can identify direct and indirect emissions from economic activities. | Requires high-quality data of input-output tables; exist problem of ‘path dependence’. | Guan et al [17]; Yang et al [35] | Capital formation & Exports, Consumption & Consumption pattern |
| LMDI | Can provide perfect decomposition; data requirements are low; results are easy to interpret. | The number of decomposing factors is limited. | Li et al [36]; Liu and Wang [37]; Dong et al [22]; Zhang et al [21]; Dong et al [31]; Zhang et al [11] | Synergistic emissions reduction, Emission intensity & Energy intensity, Emission coefficient & Economic growth, Investment scale & Emission intensity |

Table 1. Popular methods to study the influencing factors of PM\(_{2.5}\) pollution.
decrease in percentage of pollutant are caused by each 1% economic change. To avoid over-interpretation of slight changes as significant, Tapio still regarded the interval with an elasticity of 1 floating up and down by 20% as indicative of a coupling. Figure 1 shows classification standards for eight decoupling state and its economic meaning.

### 3.2. LMDI decomposition model

In order to study socioeconomic impacts of PM$_{2.5}$ emissions from the transportation sector, a decomposition model is introduced for quantitative analysis. The LMDI decomposition model can flexibly set influencing factors, decompose the residual, and avoid the problems of zero (or negative) values, so it has been widely used in the environmental research [26]. By using the LMDI method, the contributions of factors influencing PM$_{2.5}$ emissions from the transportation sector are analyzed. The governing formula is as follows:

$$PM_{2.5} = \sum_{i=1}^{n} \frac{PM_{2.5i}}{e_i} \times \frac{e_i}{E_i} \times \frac{E_i}{V_i} \times \frac{V_i}{TA_i} \times \frac{TA_i}{P_i} \times P_i \quad \text{(2)}$$

where, subscript $i$ indicates a province of China; $n$ represents the total number of provinces in the region; $PM_{2.5i}$ denotes the PM$_{2.5}$ emissions from the transportation sector in the $i$th province; $e_i$ represents the total consumption of fossil energy of the transportation sector in the $i$th province; $E_i$ indicates the total energy consumption of the transportation sector in the $i$th province; $V_i$ denotes the total turnover of the transportation sector in the $i$th province; $TA_i$ indicates the value added by the transportation sector in the $i$th province; $P_i$ denotes the total population of the $i$th province.

According to the model calculation, the change of PM$_{2.5}$ emissions from the transportation sector from the base year to the target year can be decomposed into six factors:

- **Strong decoupling**
  - Economic growth, pollution reduction
  - Weak decoupling
  - $G_{economic} > G_{pollution}$
  - Strong negative decoupling
  - $G_{economic} < G_{pollution}$

Transport turnover is the product of transport volume (persons or tons) and average distance (km). It reflects the amount of transportation workload, directly affects the energy consumption of the transportation process, and influences pollution emissions. To obtain the total turnover of transportation, it is necessary to convert the passenger turnover and then add it to freight turnover, as follows:

$$V^t = C \times V^t_p + V^t_f \quad \text{(3)}$$

where, $V^t$ indicates the total turnover (ton-km); $V^t_p$ represents passenger turnover; $V^t_f$ denotes freight turnover; $C$ is a conversion coefficient. The conversion coefficient is determined through comparing turnover per person-km (moving one person one km) with turnover of moving one ton of goods one km. The conversion coefficients for each mode of transport can be obtained China's current statistical system [40] and relevant literature [41], and are listed in table 2.

Formula (2) is simplified into formula (4):

$$PM_{2.5} = \sum_{i=1}^{n} EF_i \times ES_i \times EI_i \times TI_i \times EG_i \times P_i \quad \text{(4)}$$

Figure 1. Division of decoupling state and its economic meaning. Reprinted from [39], Copyright (2021), with permission from Elsevier. CC BY 4.0.
\[ \Delta \text{PM}_{2.5} = \Delta \text{EF} + \Delta \text{ES} + \Delta \text{EI} + \Delta \text{TI} + \Delta \text{EG} + \Delta P. \]  

To obtain the influences of each effect in the period \([0, t]\), the following formula is used:

\[ \Delta X = \sum \frac{\text{PM}_i^t - \text{PM}_i^0}{\ln \text{PM}_i^t - \ln \text{PM}_i^0} \times (\ln X_i^t - \ln X_i^0) \]  

where, \(X\) as a variable represents \(\text{EF, ES, EI, TI, EG, P}\). Among them, \(\Delta \text{EF}\) represents the emission coefficient and reflects influences of change of the energy emission coefficient on \(\text{PM}_{2.5}\) emissions; \(\Delta \text{ES}\) indicates the energy structure effect, which reveals influences of the change in the proportion of fossil energy (oil, natural gas, and coal) consumed by the transportation sector in total energy on \(\text{PM}_{2.5}\) emissions; \(\Delta \text{EI}\) denotes the technological progress effect, which is used to evaluate the effects of improvements in energy efficiency on \(\text{PM}_{2.5}\) emissions; \(\Delta \text{TI}\) denotes the transport intensity effect, which measures influences of improvement of transportation efficiency on \(\text{PM}_{2.5}\) emissions; \(\Delta \text{EG}\) represents the economic growth effect and reflects influences of economic growth on \(\text{PM}_{2.5}\) emissions; \(\Delta P\) indicates the population size effect and measures changes to \(\text{PM}_{2.5}\) emissions due to changes in the population. It should be noted: on the one hand, because the data are selected from a short research interval, \(\text{PM}_{2.5}\) emission factors associated with each separate source of energy will not fluctuate greatly due to the increase of energy utilization \([42, 43]\); on the other hand, for the time being, there remains a lack of a clear standard for \(\text{PM}_{2.5}\) emissions from vehicles in China. The change of emission factors from vehicles mainly results from the variation in the energy structure of vehicles, which is consistent with the effect of energy structure. Therefore, it is assumed that the emission factor is constant and the influence of the emission coefficient effect on \(\text{PM}_{2.5}\) emissions is always zero.

### 3.3. Data sources

According to the availability of \(\text{PM}_{2.5}\) data, some 30 provinces and cities in China from 2010 to 2017 were analyzed (excluding Tibet, Hong Kong, Macao and Taiwan data). The data related to energy consumption by the transportation sectors in these provinces and cities are sourced from China Energy Statistical Yearbook. The data on \(\text{PM}_{2.5}\) emissions from the transportation sectors are taken from the Multi-Resolution Emission Inventory for China (MEIC) developed by Tsinghua University (MEIC: www.meicmodel.org). The accuracy and reliability of MEIC datasets have been verified by satellite observations \([17, 44]\). Other data are collected from the National Bureau of Statistics of China (www.stats.gov.cn/tjsj/). In order to eliminate the influence of inflation, the added values in regional transportation sectors are adjusted to 2010 prices. In accordance with differences in economic level and geographical location, the remaining 30 provinces and cities are divided into eastern, central, and western regions according to the National Bureau of Statistics of China. The distribution of the three regions can refer to the relevant literature \([45]\).

### 4. Empirical analysis

#### 4.1. Decoupling trend between economic development and \(\text{PM}_{2.5}\) emissions

Between 2010 and 2017, the decoupling relationship between \(\text{PM}_{2.5}\) emissions and industrial development was approximately N-shaped, indicating a deteriorating trend in the transportation sector in eastern, central, and western regions (figure 2). The decoupling has changed from bad to good to bad again, and this repeated change is closely related to short-term economic fluctuations. To be specific, from 2010 to 2011, the decoupling indices in the three regions were negative, indicative of a state of strong decoupling. This finding implies that \(\text{PM}_{2.5}\) emissions decreased while developing the transportation sector, showing the most ideal decoupling state. From 2011 to 2012, the decoupling indices of the three regions ranged from 0 to 0.8, indicating a weak decoupling. This suggests that the rate of change in \(\text{PM}_{2.5}\) emissions was much slower than that of development of the transportation sector. From 2012 to 2014, the decoupling indices of the three regions gradually decreased to reach a record low (−0.46) from 2013 to 2014. However, from 2014 to 2017, the decoupling indices of the three regions gradually increased, indicative of the gradually deteriorated decoupling state. From 2016 to 2017, there was evidence of a decoupling as the eastern and central regions, and the \(\text{PM}_{2.5}\) emissions increased almost synchronously with their economic development; the expansive negative decoupling was achieved in the western region, and the \(\text{PM}_{2.5}\) emissions increased faster than the development of the transportation sector. Therefore, the decoupling relationships of the two aspects in the three regions tend to deteriorate, making it necessary to improve

| Transport form | Railways | Highways | Waterway | Aviation |
|----------------|----------|----------|----------|----------|
| C              | 1        | 0.1      | 0.33     | 0.072    |
the decoupling and mitigate the continuous growth of PM$_{2.5}$ emissions in the future.

As shown in figure 3, from the time dimension analysis in the medium term (2–3 years), the decoupling state of the transportation sector has mostly changed from strong decoupling to weak decoupling, that is, the growth rate of PM$_{2.5}$ emissions becomes higher than that of the transportation sector. The decoupling state deteriorates, which can further prove the correctness of the short-term decoupling results.

### 4.2. Influence factors for growth of PM$_{2.5}$ emissions in regions

To elucidate the mechanisms of influence on PM$_{2.5}$ emissions from the transportation sector, the growth of PM$_{2.5}$ emissions is decomposed into an energy structure effect ($\Delta$ES), technological progress effect ($\Delta$EI), transport intensity effect ($\Delta$TI), economic growth effect ($\Delta$EG), and population size effect ($\Delta$P) from 2010 to 2017. As demonstrated in figure 4, emission incremental effects in the eastern and central regions are greater than emission reduction effects, PM$_{2.5}$ emissions thus increase; in the western region, each effect is relatively small and finally the emission reduction effect is greater than the emission increment effect. Specifically, the energy structure effect and transport intensity effect are emission reduction effects, while the economic growth effect and population size effect are emission increment effects. In eastern and western regions, the technological progress effect is one of emission reduction, while it increases emissions in the central region.

Due to the different levels of economic development in eastern, central, and western China, there may be differences in the economic implications reflected by the absolute and relative values (contribution rate) of the LMDI decomposition results. Herein, the contribution rate index is used to compare the influences between regions, thus eliminating the uncertainty of the decomposition results caused by different levels of economic development. In addition, different LMDI decomposition periods will also produce a little differences in decomposition results (see figure 5), but this does not change the main conclusions of the article. Next, we will analyze the mechanism of the influencing factors of long-term results.

#### 4.2.1. Emission reduction effect

The emission reduction effects of the energy structure effect on PM$_{2.5}$ emissions from the transportation sector mainly benefit from the optimization of the energy consumption structure. The emission reductions arising therefrom in the eastern, central, and western regions are 55, 89, and 37 thousand tons, respectively. The contribution rates of energy structure effect on PM$_{2.5}$ emissions in the eastern, central, and western regions of China are $-1272\%$, $-802\%$, and $-722\%$ respectively. The energy structure refers to the proportion of fossil energy (oil, gas, and coal) in the total energy mix and describes the cleanliness.
of the energy consumption structure. As shown in figure 6, the proportions of fossil energy in the eastern, central, and western regions of China separately were decreased by 5%, 7%, and 3% from 2010 to 2017. The lower the proportion of fossil energy in the transportation sector, the cleaner the energy consumption structure, and the lower its pollution emissions.

In addition, PM$_{2.5}$ emissions contain many harmful substances, which are mainly divided into heavy metal pollution (such as Cd, Hg, As, Cr, etc) and organic pollution (such as polycyclic aromatic hydrocarbons). Different proportions of harmful components in PM$_{2.5}$ will cause different degrees of harm to human health [46]. Studies have shown that the
harmful substances and health hazards caused by fuel oil are generally greater than those caused by burning coal [47]. In China’s transportation sector, the proportion of fuel used in the east is larger than that in the central and western regions. Therefore, in the case of the same total emission, PM$_{2.5}$ produced by the eastern transportation sector may cause greater health hazards. Fully adjusting the energy structure cannot only reduce emissions, but also reduce health risks.

The emission reduction effects of the transport intensity effect on PM$_{2.5}$ emissions from the transportation sector are mainly due to the improvement of transportation efficiency. The emission reductions due to the effect in the eastern, central, and western regions reach 69, 59, and 37 thousand tons, respectively. The contribution rates of transport intensity effect on PM$_{2.5}$ emissions in the eastern, central, and western regions of China were $-160\%$, $-53\%$, $-70\%$ respectively. The transport intensity is defined as the turnover per unit of economic output. If this factor promotes emission reductions, it means that the turnover required to produce economic output per unit decreases, the transportation efficiency increases, and energy consumption and pollution per unit transportation decrease [15]. The possible reasons for this are that, on the one hand, the energy consumption per capita associated with buses and subway systems in China is 17% and 2.4% of that of cars, respectively [48]. The development of public transportation saves energy costs, effectively diverges private transportation and realizes environmental protection to a certain extent; on the other hand, with the continuous integration of ‘Internet + Logistics’, transportation resources are integrated to reduce unnecessary transportation service and improve transportation efficiency. The improvement of the transportation efficiency implies a concomitant decrease in transportation costs. The proportion of transportation costs in China in gross domestic product decreased from 21.3% in 2010 to 14.7% in 2019. However, in 2019, the proportion still showed a gap with 7.6% of the USA [49]. This result implies that there is still considerable scope for optimizing transportation routes in China.

4.2.2. Emission increment effect

The emission increment effects of the economic growth effect on PM$_{2.5}$ emissions from the transportation sector are mainly caused by rapid economic development, which is consistent with conclusions reached by Chen et al [1]. Rapid economic development inevitably consumes much energy and materials and promotes continuous growth in emissions.
of PM$_{2.5}$. The increments of PM$_{2.5}$ emissions in the eastern, central, and western regions are 149, 107, and 74 thousand tons, and the contribution rates of economic growth effect on PM$_{2.5}$ emissions in the eastern, central, and western regions of China were $-3451\%$, $-972\%$, $-1432\%$ respectively. The contribution rates show a trend of high contribution in the east. Because development in the eastern region is always outpacing than that in the central and western regions, the increase of car ownership and construction of transportation infrastructures are fast in the east and slow in the west [8]. Therefore, the energy consumption and pollution emissions caused by PM$_{2.5}$ emissions in the transportation sector are high in the east and low in the west of China.

The emission increment effects of the population size effect on PM$_{2.5}$ emissions from the transportation sector mainly result from population inflow. More population inflows mean higher proportional travel and transportation demands, which accelerates energy consumption and PM$_{2.5}$ emissions. The increment of PM$_{2.5}$ emissions in the eastern region is 11 thousand tons, which is much higher than those in the central (4 thousand tons) and western (5 thousand tons) regions. And the contribution rates of population size effect on PM$_{2.5}$ emissions in the eastern, central, and western regions of China were $-251\%$, $-37\%$, $-98\%$ respectively. The main reason for this is that the eastern region shows advantages in economy, technology, and policy terms [22], and therefore accrues a greater population influx than central and western regions, resulting in more pollution emissions.

4.2.3. Uncertain effect: the technological progress effect

Technological progress is measured by energy consumption per unit turnover, and the lower the energy consumption per unit turnover, the higher the technical level of the region [50]. The technological progress effect is divided into the ‘technological effect’ and ‘rebound effect’. On the one hand, technological progress can improve the energy efficiency and reduce unit energy consumption [31] and pollution emissions in the transportation sector (the so-called ‘technological effect’). On the other hand, technological progress can reduce the real price of energy [51], which stimulates new demand for transportation services [52] and leads to a new round of energy consumption and pollution emissions (the ‘rebound effect’). Therefore, the influences of technological progress are finally evaluated by the relative sizes of the ‘technological effect’ and ‘rebound effect’.

In the transportation sector, technological progress separately reduces PM$_{2.5}$ emissions by 31 and 11 thousand tons in the eastern and western regions, while increasing them by 47 thousand tons in the central region. The contribution rates of technological progress effect on PM$_{2.5}$ emissions in eastern, central and western China are $-727\%$, $427\%$ and $-203\%$ respectively. This finding indicates that the ‘technological effects’ are greater in the eastern and western regions, while the ‘rebound effect’ is greater in the central region. The main reason for this is that the research and development (R & D) capability is strong in the eastern region, whereas there is much room for improvement with respect to
technological progress in the western region, so the ‘technological effect’ is dominant in the two regions [52, 53]. However, the R & D capacity and space for technological progress are limited in the central region, market-oriented reform of energy resources lags, and the oil price is lower than that of other markets [54]. As shown in figure 7, the average price of gasoline in central China is always lower than that in the east and west. In this case, it is more vulnerable to the influence of oil price to produce new transportation demand, resulting in the significant rebound effect in the central region of China. In research into urban transportation [51, 55], the presence of this significant rebound effect in the central region of China has been verified.

5. Conclusions and policy suggestions

The decoupling relationships between PM$_{2.5}$ emissions and economic growth from the transportation sector in the eastern, central, and western regions of China and their influencing factors are studied by combining the Tapio decoupling model and LMDI model. The main conclusions are as follows:

(a) In the transportation sector, the decoupling state in the three regions show an N-shaped trend from 2010 to 2017. The strong decoupling becomes an expansive coupling in the eastern and central regions, while the strong decoupling becomes an expansive negative decoupling in the western region. The decoupling statuses tend to deteriorate in the three regions.

(b) Energy structure effect and transport intensity effect are emission reduction factors. Economic growth effect and population size effect are factors that increase emissions. Based thereon, improving the energy structure and reducing transport intensity are the key to restraining growth of PM$_{2.5}$ emissions from the transportation sector.

(c) Technological progress can result in the large rebound effect in the central region, which leads to development of new transportation services, causing increased levels of haze arising from PM$_{2.5}$ emissions. On the contrary, technological progress improves energy efficiency and reduces pollution in the eastern and western regions.

Based on these conclusions, PM$_{2.5}$ emissions should be reduced as much as possible while maintaining economic growth. The following policy suggestions are proposed:

(a) Improving the energy structure of vehicles. In 2020, the prevalence of new-energy vehicles is low (5.4%) in China, so government should strengthen efforts to shift hydrocarbon-fuelled vehicle use to new-energy vehicle use as much as possible. Specifically, government can increase the prevalence of new-energy vehicles through tax reduction, subsidies, and policy support.

(b) Improving the efficiency of the transportation system. On the one hand, government should reasonably add buses, subways, and urban railways, and increase commuting concessions for public transportation. Meanwhile, the public is called on to adopt low-energy travel modes, such as walking, cycling, and on-line interaction. On the other hand, with the development of e-commerce, there is significant scope for the improvement of logistics service demands. Government needs to optimize the storage system, ameliorate transportation paths for inventory and shorten the supply chain, so that excessive transportation is avoided. In addition, government departments should also optimize traffic layouts, increase linear traffic routes, and reduce unnecessary transportation in combination with urban and rural policies and the current land-use situation.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Author contributions

Y W: conceptualization. Y W and Y Z: methodology. Y Z: software. B X: validation. Y W: formal analysis. Y Z: data curation. Y W, Y Z and B X: writing & editing. Y Z and B X: visualization. Y W: funding acquisition. All authors contributed to the article and approved the submitted version.
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