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Cost–Benefit Analysis of Synergistic CO_2 and NO_x Energy-Efficient Technologies for the Road Transport Sector in China

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Abstract: The transportation sector is a major source of greenhouse gases and air pollutants, and it has a crucial effect on the synergistic reduction of NO_x and carbon. In order to find the energy-efficient vehicle technologies with the highest net reduction potential and lowest net reduction cost over the life cycle, this study traced the CO_2 and NO_x emission streams of 33 energy-efficient technologies, hidden in the supply chain during the production phase, through structural path analysis, and measured the emission reductions during the use phase using the emission factor method. Moreover, we applied structural decomposition analysis to quantify the three main drivers, including emission intensity, industrial structure, and final demand, of changes in CO_2 and NO_x emissions from 11 transport subsectors during 2012–2018. Results indicate that CO_2 emissions of the transport sector more than doubled from 2012 to 2018; however, the influence of NO_x was less significant. The final demand of the road subsector was the most significant driver contributing to CO_2 emission changes, with an increase of 109.27 Mt. The emission intensity of road transportation caused the greatest mitigation effect on NO_x emission changes, with a decrease of 1902 Kt. The findings of the scenario analysis demonstrate that the most efficient action of the pure electric technology for passenger cars reduces 20.92 Mt NO_x emissions, and the parallel hybrid technology for heavy trucks offers the greatest cost effectiveness with a net abatement of 2577 Mt CO_2 over its life cycle. Consequently, the aggressive development of new energy technology has become a prerequisite strategy to synergistically reduce CO_2 and NO_x emissions.

Keywords: transport sector; input–output analysis; structural decomposition analysis; structural path analysis; life cycle assessment; net abatement cost

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1. Introduction

Transportation is a demand-derived source of mobility that facilitates economic activity by linking the production, exchange, consumption, and distribution of goods or services in society. Transportation ensures the proper conduct and development of economic activity and plays an important role in the economic activity of society. However, as the economy grows, China's environmental pollution problem has attracted widespread attention. To address this serious pollution problem, the State Council of China promulgated the toughest ever Air Pollution Prevention and Control Action Plan in 2013.

With the implementation of this policy from 2013 to 2017, air quality has improved significantly nationwide [1]. However, the transportation sector remains a major contributor to CO_2 and NO_x emissions [2,3]. Therefore, analyzing the change in emissions in the transport sector from 2012 to 2018 and its main drivers would inform the development of future emission reduction pathways, while finding the most cost-effective and emission-reducing potential technologies for the most prominent emission subsector (the road transport sector) is essential to reduce emissions from the transport sector in the future.

A large number of existing studies analyzed the abatement costs and reduction potential of various energy-efficient technologies for vehicles. For example, the International Council on Clean Transportation (ICCT) examined the emission reduction potential and abatement costs of a variety of technologies, including passenger cars and trucks, over a fifteen-year period from 2015 to 2030 [4,5], and they found that the larger the reductions, the higher the cost of the required technology investment. However, consumers may also gain benefits through fuel cost savings, which will be two to three times the cost of investment by 2030 due to technology implementation [5]. Peng et al. [6] studied 55 energy-efficient technologies related to passenger cars in China from 2010 to 2030, whose findings showed that new energy technologies, including electric and hybrid electric vehicles, have the greatest abatement potential but the highest abatement costs. Of all the technologies, only a few technologies can reap the benefits while reducing emissions. In addition, technologies with low abatement costs would reduce abatement potential. Some studies [7–9] researched the cost-effectiveness of new energy vehicles in terms of greenhouse gas emission reduction; their findings also showed that electric vehicles have high greenhouse gas reduction potential but a poor ability to be cost-effective. The net abatement cost, as a result of the above study, is uncertain, due to the fact that it is determined by several factors, including investment costs and oil prices. However, the general rule is that investment costs increase with the amount of abatement, and oil prices have a strong influence on whether energy efficiency technologies require costs or return benefits.

At the same time, energy-efficient technologies may produce significant emissions in the production phase. Rosenfeld et al. [10] showed that new energy vehicles have high CO_2 emissions in the production phase, especially pure electric vehicles, whose emissions in the production phase can reach half of the emission reductions in the use phase. In the coming decades, with the advancement of technology, the use phase of new energy vehicles may have a higher emission reduction potential, and the production phase may become the main stage of pollutant emissions during its life cycle. In addition, the results of Zhu et al. [11] showed that the impact of greenhouse gases on global temperature has a lag. That is, the production emissions now will affect the temperature in the next decades. Therefore, emissions from the production phase of emission reduction technologies cannot be ignored. Inadequately, most of the available studies focused on the research of the use stage of the treatment technology of vehicles, but rarely analyze the whole life cycle of vehicle emission reduction technology.

To make up for this research gap, based on the input–output model, we applied the structural path analysis (SPA) method to study the emission abatement potential and cost of 33 technologies, including the whole life cycle of production and consumption (i.e., the use stage). SPA is a suitable tool for linking emissions from various sectors of the national economy and revealing the flow of emissions from the product to the consumer [12,13]. SPA is a widely used tool to study the emission pathways of greenhouse gases and pollutants, such as CO_2 [14,15], particulate matter ($PM_{2.5}$) [16,17], SO_2 [18], and so on. Therefore, it is feasible to use SPA to measure the implied emission streams in the economic system due to the implementation of energy-efficient technologies in the transport sector. In terms of emission objects, the current study selected the greenhouse gas CO_2 and the air pollutant NO_x. The transport sector is the main source of these two emissions.

By analyzing the emission abatement potential and cost of various vehicle energy-efficient technologies, the results of present study aimed to provide a scientific basis for the energy-efficient technologies that may help reduce air pollution, and to, consequently, help the Chinese government to choose and promote cost-effective and environmentally friendly technologies.

2. Methods and Data

In the current study, a number of variables were used to study the abatement costs and abatement potential of the transport sector. Their descriptions and notations are summarized in Table 1.

Table 1. List of variables and symbols.

Variable Name	Symbol	Variable Name	Symbol
Direct emission coefficient	θ	Vehicle ownership	*VO*
Total output column vector	*X*	Average annual mileage	*AM*
Complete demand factor matrix	$(I - A)^{-1}$	Fuel density	ρ
Final demand column vector	*Y*	Power consumption per unit mileage	*PM*
Pollutant emissions	*E*	Oil price	*OP*
Amount of change	Δ	Electricity price	*EP*
Production layer	*PL*	Investment cost	*IC*
Direct emissions	D^t	Final demand of reduction in the refined petroleum sector	y_1
Indirect production embodied emissions	P^t	Final demand of increases in the related industries of auto parts sector, rubber, and complete vehicle manufacture sector	y_2
Consumption emissions	E^t	Final demand of increases in the electricity sector	y_3
CO_2 generation factor	α	Additional emissions from the implementation of emission reduction technologies through industry linkages	AP_P
Engine efficiency	*S*	Direct emission abatement during the use phase of the technology	AP_U
Annual statistical NO_x emissions	β	Net emission abatement potential from LCA perspective	AP_{net}
Fuel economy	*FE*	Net abatement benefit	*NB*

2.1. Methods

The structural decomposition analysis (SDA) and structural path analysis (SPA) models were applied to extend the decomposition of CO_2 and NO_x emission structure based on the input–output (IO) model. The IO model was proposed in the 1930s by the American economist Wassily Leontief and has been widely used in a variety of disciplines affected by economic activity, especially the environmental impact of economic activity. We assumed that the IO table contains n industries, and the IO table can be represented as:

$$\begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{12} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{pmatrix} \times \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix} + \begin{pmatrix} f_1 \\ f_2 \\ \vdots \\ f_n \end{pmatrix} \quad (1)$$

Equation (1) can also be expressed as follows:

$$\begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix} = \begin{pmatrix} 1 - a_{11} & -a_{12} & \cdots & -a_{1n} \\ -a_{12} & 1 - a_{22} & \cdots & -a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ -a_{n1} & -a_{n2} & \cdots & 1 - a_{nn} \end{pmatrix}^{-1} \times \begin{pmatrix} f_1 \\ f_2 \\ \vdots \\ f_n \end{pmatrix} \quad (2)$$

Equations (1) and (2) are the core formulas of the input–output table, where $X = (x_i)$ is the total output of industry *i*; $A = (a_{ij})$ is the amount of value per unit of output consumed by sector *j* for product *i*; and $F = (f_i)$ is the final demand of sector *i*.

2.1.1. Structural Decomposition Analysis (SDA)

In the present study, SDA was used to analyze the drivers of changes in CO_2 and NO_x emissions in the transport sector. SDA was proposed by Chang and Lin [19] to evaluate the factors affecting changes in industrial greenhouse gas emissions in Taiwan, decomposing emissions into multiple drivers during 1981–1991. Since SDA can provide detailed information about structural factors, it has been widely applied to explore the influencing factors [20–22].

SDA is commonly used to examine the contribution of potential drivers to changes in observed indicators in IO tables [23]. SDA calculates the contribution of each independent variable to the dependent variable by considering the changes in each independent variable in a different way.

To assess the driving forces, the pollutant emissions (E) are decomposed into emission intensity (θ), industry structure $(I - A)^{-1}$), and final demand (F).

$$\Delta E = E_{t+1} - E_t = \theta_{t+1}(I - A)^{-1}_{t+1} Y_{t+1} - \theta_t (I - A)^{-1}_t Y_t \tag{3}$$

$$\Delta E = \Delta\theta (I - A)^{-1}_{t+1} Y_{t+1} + \theta_t \Delta (I - A)^{-1} Y_{t+1} + \theta_t (I - A)^{-1}_t \Delta Y \tag{4}$$

where, Δ denotes the amount of change; for example, ΔE denotes the change in pollutant emissions between 2012 and 2018, $t + 1$ denotes 2018, and t denotes 2012.

2.1.2. Method of Measuring Cost–Benefit

The cost of abatement is an important consideration for companies, sectors, and regions when determining the pathways of mitigating emissions. As the road is the highest CO_2- and NO_x-emitting transport subsector, the search for the most efficient and least costly abatement technology for vehicles is a critical issue, which facilitates the opportunity to design sensible, model-specific mitigation strategies.

Currently, China has different scrappage regulations for different vehicle types, with 15 years for light trucks and heavy trucks, and 15 years or longer for passenger cars, which have no specific time limit. Therefore, for the convenience of accounting, the service life of all three models studied in this study was set to 15 years [24]. In the present study, the intensity of emissions by sector and the supply relationship between sectors were assumed to remain constant over the life cycle of vehicle use (i.e., 15 years), and similar assumptions have been set in many studies [25–27].

Cost–benefit analysis methods have been widely applied in the field of environmental decision-making, where they are used to quantify the costs and benefits of different policy actions or abatement technologies in order to obtain optimal decisions. The study considered three types of costs, including technology investment costs (f_1), fuel-saving benefits (f_2), and electricity costs (f_3), of which investment costs are one-time, and fuel savings and electricity costs are cumulative over the life cycle of technology implementation. Therefore, we did not consider discounting for the technology investment costs (f_1), while setting the fuel-saving benefit (f_2) and electricity cost (f_3) increases at a discount rate of 5% over 15 years [6]. These three costs or benefits (*in million yuan*) can be calculated as follows:

$$f_1 = IC \times TO \times 10^{-6} \tag{5}$$

$$f_2 = \sum_{i=1}^{15} (TO \times FE \times TM \times FC \times S \times 10^{-6} \times (1 + 5\%)^{14}) \tag{6}$$

$$f_3 = \sum_{i=1}^{15} (TO \times PE \times TM \times EC \times 10^{-6} \times (1 + 5\%)^{14}) \tag{7}$$

where IC (yuan) is the investment cost of each technology installed in each vehicle. TO is the total ownership of the three categories studied in this paper as of the end of 2018. FE is the fuel efficiency per unit mileage (L/km). PE is the power efficiency per unit mileage (kW·h/km). TM is the total mileage over the life cycle (km). FC (yuan/L) is the cost per liter of fuel; the price per liter of diesel was 6.88 yuan, and the average price per liter of gasoline was 7.27 yuan in China in 2018 [28]. EC is the cost per kW·h of electricity (yuan/kW·h), and the average electricity price in China in 2018 was 0.374 yuan/kW·h [29]. S is the energy efficiency in %. The parameters of FE, PE, TM, and VO are listed in Table 2. IC and S are given in Table 3.

Table 2. Parameters of the three types of vehicles.

Tape	*VO* [30] (Million Vehicles)	*TM* [31] (10^4km)	*FE* or *PM* [32] (per km)
Passenger Car (Fuel)	227.7	27	0.092 L
Passenger Car (Electric) [33]	/	14.9	0.164 kW·h
Light Truck	100.96	45	0.205 L
Heavy Truck	80.84	113	0.297 L

If a technology could be economically beneficial while still fulfilling its intended role, this would go a long way toward reducing resistance to technology implementation. Existing studies generally discuss emission reductions from a cost perspective. However, considering the potential economic benefits of a large number of energy efficiency technologies studied in this paper, we used benefits as an economic indicator for each technology, and the net benefits (NB) are as follows:

$$NB = f_3 - f_1 - f_2 \tag{8}$$

Table 3. Energy saving rate and emission reduction efficiency of 33 technologies. This table shows the technology name, saving efficiency, investment costs, and code.

	Passenger Car [6,34]				Light Truck [35]				Heavy Truck [36]			
	Technology Name	**Saving Efficiency**	**Investment Costs (Yuan/Vehicle)**	**Code**	**Technology Name**	**Saving Efficiency**	**Investment Costs (Yuan/Vehicle)**	**Code**	**Technology Name**	**Saving Efficiency**	**Investment Costs (Yuan/Vehicle)**	**Code**
Engine Technology	Engine Friction Reduction	1.50%	820.56	PC1	Engine Friction Reduction	2.00%	463.22	LT1	Advanced 6–9 L Engine	16.07%	66,174.00	HT1
	Variable Valve Timing—Dual Cam Phasing	2.50%	403.66	PC2	Continuous Variable Valve Lift	2.17%	3176.35	LT2	Advanced Transmission and Drivetrain	4.90%	10,146.68	HT2
	Continuous Variable Valve Lift	2.50%	2024.92	PC3	Chemometric Proportioning —Direct Gasoline Injection	1.50%	2438.51	LT3	Parallel Hybrid	29.33%	130,142.20	HT3
	Chemometric Proportioning—Direct Gasoline Injection	2.40%	2425.28	PC4	Turbocharging and Miniaturization	6.25%	2316.09	LT4	10% Air Resistance Reduction	4.50%	11,084.15	HT4
	Turbocharging and Miniaturization	4.85%	8093.08	PC5	High-Efficiency Generator and Accessory	1.50%	959.52	LT5	Low Rolling Resistance Tire	2.47%	1345.54	HT5
	Electric Power Steering	1.50%	747.77	PC6	Electric Power Steering	2.00%	1042.24	LT6	3% Lightweight	2.65%	22,366.81	HT6
	High-Efficiency Attachment	1.50%	1270.54	PC7								
New Energy technology	Dieselization	15.20%	20,570.19	PC8	Power Split Hybrid	6.50%	24,980.69	LT7	Parallel Hybrid	29.33%	130,142.20	HT3
	Advanced Dieselization	10%	3441.05	PC9	Plug-in Hybrid	29.00%	52,277.46	LT8				
	General Hybrid	13.70%	17,160.24	PC10								

	Plug-in Hybrid	62%	150,649.08	PC11								
	Pure Electric	100%	208,978.42	PC12								
Drag reduction technology	Low-Friction Lubricant	0.50%	33.09	PC13	Low-Friction Lubricant	0.50%	19.85	LT9	10% Air Resistance Reduction	4.50%	11,084.15	HT4
	5% Lightweight	3.30%	1581.56	PC14	10% Air Resistance Reduction	2.33%	248.15	LT10	Low Rolling Resistance Tire	2.47%	1345.54	HT5
	Low Rolling Resistance Tire	1.50%	49.63	PC15	Low Rolling Resistance Tire	1.50%	39.70	LT11	3% Lightweight	2.65%	22,366.81	HT6
	10% Air Resistance Reduction	2.50%	582.33	PC16								
	Low Rolling Resistance Tire	1.50%	49.63	PC15								
	10% Air Resistance Reduction	2.50%	582.33	PC16								

2.1.3. Methodology of Structural Path Analysis (SPA) and Measuring of Net Abatement Potential

Not only economy is an important reference factor in choosing an abatement technology, but the abatement potential is equally important. Facing the current severe environmental pressures, it is optimal to find technologies that have high economic efficiency and a high potential to reduce emissions. For this purpose, we measured the direct and embodied emissions of the entire economy during the production phase of the abatement technology, using the structural path analysis (SPA) method. We used the investment costs (f_1), fuel benefits (f_2), and electricity costs (f_3) of 33 specific energy-efficient technologies as the final demand variation parameters for the SPA methodology to evaluate the CO_2 and NO_x emissions in the production phase.

Skelton et al. [13] extended the application of traditional structural path analysis (SPA) methods in the environmental domain. The extended SPA approach can trace the complex relationships between sectoral interactions and embodied emission streams, as well as investigate the differences between final production emissions and final demand emissions and the reasons for their formation. SPA models, which can show detailed flow path maps of the supply chain between final production and consumption, have been widely used to identify key sectors and supply chain pathways leading to energy consumption and pollutant emissions [37,38]. This approach can effectively quantify demand-driven environmental emissions.

The SPA approach relies on the Leontief inverse matrix, which is able to systematically identify key impact sectors or pathways through decomposition. The decomposition of the Leontief inverse matrix $(I - A)^{-1}$ is expressed as follows:

$$(I - A)^{-1} = lim_{t\rightarrow\infty} I + A + A^2 + A^3 + \ldots + A^t \tag{9}$$

Then, the input–output model can be expressed as:

$$X = \theta(I - A)^{-1}F = lim_{t\rightarrow\infty}(\theta IF + \theta AF + \theta A^2F + \theta A^3F + \ldots + \theta A^tF) \tag{10}$$

where θ is the emission intensity, that is, the pollutant emissions per unit of output, and, in this paper, is the emission intensity of CO_2 and NO_x. In Equation (10), θA^iF represents the impact from the production sector at level i. For example, when F represents the demand for the production of a car, θIF is the direct emission of the producer in the production process; in order to produce the car, other sectors need to input AF, which generates the emission of θAF; the increased input of other sectors further requires the production input of A^2F, which continues to generate the emission of θA^2F. This process continues through the infinite expansion of the power of the Leontief inverse matrix, and eventually, the total direct and implicit emissions from the production of a car are decomposed in layers to obtain all emission paths.

This study quantified the emissions of energy-efficient technologies in the production phase (AP_P), using the extended structural path analysis (SPA) method described above, including the additional emissions generated by the technology itself in the manufacturing process (E_{tech}), the additional emissions of the electricity required in the use phase of the abatement technology in the production phase (E_{elec}), and the reduction in emissions from the fuel saved by the energy savings of the abatement technology in the production phase (E_{fuel}).

$$AP_P = E_{tech} + E_{elec} - E_{fuel} \tag{11}$$

The coefficient method is a common accounting method for the total amount of pollutants. In the use phase of the abatement technology, we used the coefficient method to estimate the CO_2 and NO_x emissions. We obtained the CO_2 reduction (AP_{U-CO_2}) by multiplying the CO_2 production factor of the fuel (gasoline or diesel) by all the fuel saved by the technology during the use phase. As vehicle NO_x is more likely to be influenced by exhaust gas control technologies, the relationship between its production and fuel consumption is currently uncertain. Therefore, in the absence of sufficient data, this study obtained the NO_x use phase emission reductions (AP_{U-NOx}) by multiplying the emissions before technology implementation by the corresponding energy efficiency of the 33 technologies.

In summary, we obtained additional emissions in the production phase based on the SPA method, and emission reductions in the use phase based on the coefficient method, and the net emission abatement potential (AP_{net}, CO_2 in Mt, and NO_x in Kt) over the life cycle of the energy-efficient technology can be expressed as:

$$AP_{net} = AP_U - AP_P \tag{12}$$

2.2. Data

2.2.1. Input–Output Table and Pollutant Emission Data

The 2012 input–output tables and 2018 input–output tables used in this study were obtained from the National Bureau of Statistics of China [39]. The transportation sector in this study included 11 subsectors, including passenger and freight transport by rail, road, water, and air, as well as pipeline transport, multimodal transport, and postal services.

Since the transportation sector is the most important source of NO_x, we only considered NO_x in this study. The data of NO_x emissions for vehicles (the road passenger transport subsector and road freight transport subsector) were obtained from the Annual Report on Environmental Management of Mobile Sources in China [40]; among them, the tailpipe NO_x emissions in 2018 were 600 Kt for passenger cars, 276 Kt for light trucks, and 3513 Kt for heavy trucks. NO_x emission data for other sectors were obtained from the National Bureau of Statistics of China [39]. The CO_2 emission accounting process in this paper used energy consumption data by sector from CEADs [41] and CO_2 generation factors from the Intergovernmental Panel on Climate Change (IPCC) [42].

2.2.2. Basic Data of Energy-Efficient Technologies

For the future development of automotive emission reduction technology, the "New Energy Vehicle Industry Development Plan (2021–2035)" in China clearly states that new energy vehicles (e.g., pure or plug-in electric vehicles, hybrid vehicles, and fuel cell vehicles) and general-purpose body and engine technologies (such as lightweight technologies and low frictional resistance technologies) are the future direction of development [43]. However, there is a lack of systematic and published data for these technologies in China. Here, the parameters of energy-efficient technologies for trucks refer to the reports of the National Science Research Council and the National Highway and Traffic Safety Administration [34–36], and the parameters of passenger cars refer to the study of Peng et al. [6] and the report of the National Highway and Traffic Safety Administration [34].

3. Results and Discussion

3.1. Change and Driving Force Analysis of CO_2 and NO_x Emissions in the Transport Sector

The Air Pollution Prevention and Control Action Plan (the Action Plan) put forward a series of requirements to reduce emissions from transportation sources, such as improving fuel quality and phasing out yellow-label vehicles by a deadline [44]. We analyzed the changes of CO_2 and NO_x emissions in 11 subsectors of transportation and their drivers before and after the implementation of the Action Plan.

Based on CO_2 and NO_x emissions from 11 transport subsectors over the period of 2012–2018, our results showed that CO_2 emissions from the transport sector increased significantly, while NO_x emissions remained largely flat (Figure 1). The largest contribution to the increase in CO_2 emissions was made by the road freight transport sector, which accounted for about 40% of the increase, followed by the multimodal transport subsector and the road passenger transport subsector, which accounted for 29.42% and 12.87%, respectively. NO_x reductions in the road freight transport sector had a significant impact on NO_x flatness in the transport sector, with an 8.65% reduction from 2012–2018.

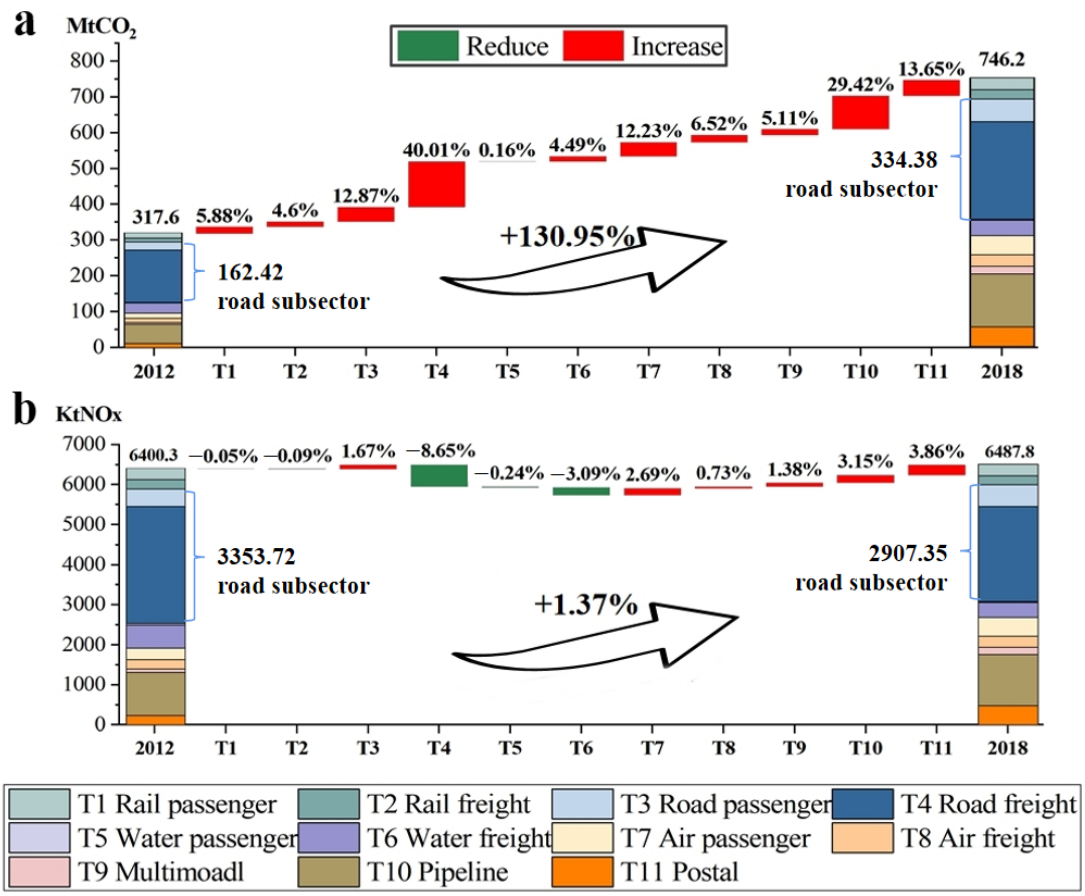

Figure 1. Changes in CO_2(**a**) and NO_x (**b**) emissions in the transport sector from 2012 to 2018.

In addition, our study used the structural decomposition analysis (SDA) method to analyze the drivers of change in emissions in the transport sector. The SDA has been widely used to investigate emissions to identify drivers of CO_2 and NO_x emission change, based on input–output models of analysis [20–22,45]. We exposed the impact of emission intensity, industrial structure, and final demand as drivers of CO_2 (a) and NO_x (b) emission changes (see Figure 2).

As shown in Figure 2, the drivers of final demand played positive roles in increasing CO_2 and NO_x emissions over the study period, leading to an increase of 236.67 Mt CO_2 and 4769.7 Kt NO_x in the transport sector. In particular, the road subsector had the largest increase in emissions due to final demand factors, with an increase of 109.27 Mt CO_2 and 781.41 Kt NO_x. The industrial structure also had an impact on the growth of emissions in the total transport sector, with an increase of 26.78 Mt CO_2 and 539.7 Kt NO_x compared to 2012. However, from 2012 to 2018, the industrial structure also had a negative impact on some subsectors, especially the road freight subsector, which mitigated 21.29 Mt CO_2 and 429.07 Kt NO_x. Emission intensity had a different impact on CO_2 and NO_x, with an increase of 165.12 Mt CO_2 but a decrease of 5221.60 Kt NO_x from 2012.

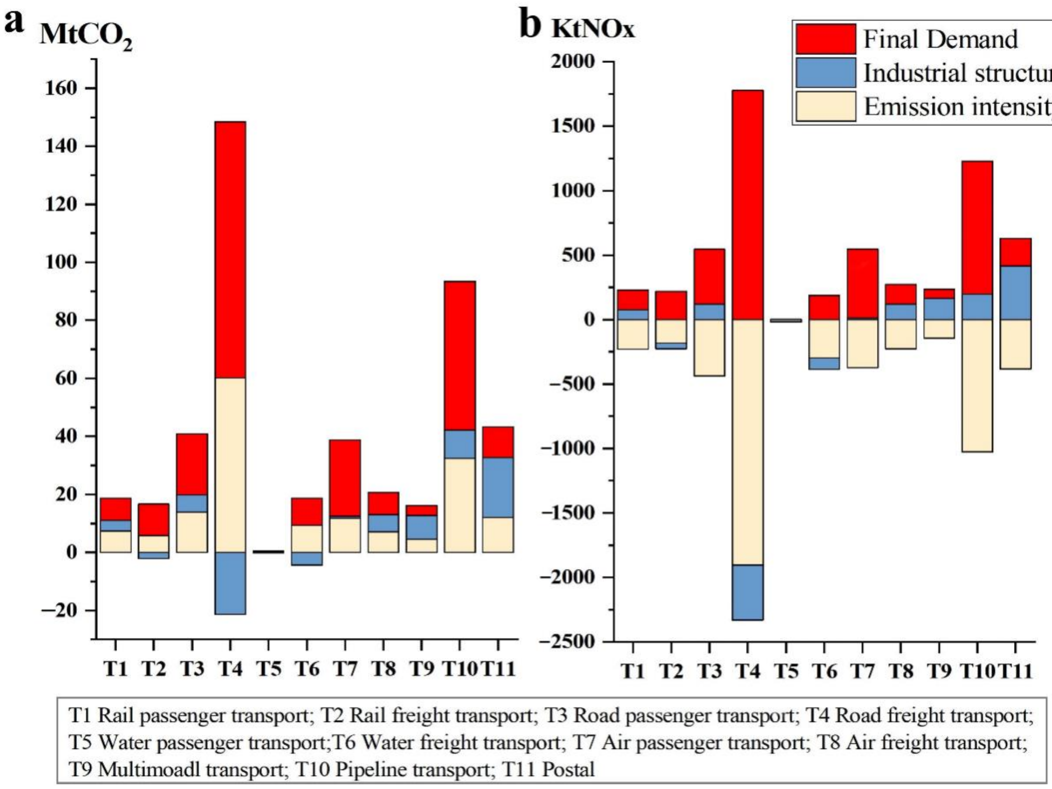

Figure 2. Contribution of three main drivers of CO_2 (**a**) and NO_x (**b**) emission change in 11 transport subsectors from 2012 to 2018.

Among all studied factors, the increased emissions of both CO_2 and NO_x that were due to final demand were the highest. From 2012–2018, China's demand for the transport sector increased dramatically, leading to significantly increased emissions. In the road subsector, for example, China's car ownership per 1000 people is much lower than in developed countries [46], which means that with China's rapid economic development, in the foreseeable future, there will be an inevitable trend toward swelling car ownership. The study also found that the intensity of CO_2 emissions was also a factor contributing to the increase in emissions during its study period (Figure 2a). However, the increase in final demand was offset by a reduction in the intensity of NO_x emissions (Figure 2b). Environmental policies may be the main reason for the opposite trend of NO_x and CO_2 emissions. From 2013 to 2018, China became very stringent in managing transport NO_x emissions, especially for the road subsector, the main emission subsector of the total transport sector, which has entered deep water. A range of vehicle end-of-pipe policies have helped to achieve significant NO_x reductions, such as improved fuel quality for energy efficiency [47], the installation of exhaust treatment units, and stricter exhaust emission standards [48].

In the future, emissions from motor vehicles will remain high, as will other transport subsectors. Therefore, there is an urgent need to find effective ways to reduce emissions; perhaps the use of cost-effective and high abatement potential technologies could help reduce CO_2 and NO_x emissions.

3.2. Cost–Benefit Analysis of Energy-Efficient Technologies

Assessing the net abatement potential and economic costs of mainstream vehicle energy efficiency technologies can provide data to support and inform the planning of low-carbon investments and policies in China's road transport sector. We calculated the net abatement potential (AP_{net}) of 33 road transport technologies using cost–benefit analysis and the SPA method (see Figure 3), which includes both additional emissions from the production phase and direct reductions from the use phase. This allows emissions directly from the technology, electricity, and oil production stages, and indirectly through the supply chain, to be taken into account.

The results showed that most the studied technologies had good synergistic CO_2 and NO_x reduction effects. Overall, passenger cars and heavy trucks had a high potential to reduce emissions. Of these, new energy technologies (T-II) were more prominent in all three categories, as shown in Figure 3. Among all energy-efficient technologies, the pure electric technology for passenger cars (PC12) had the highest net NO_x reduction potential, and the parallel hybrid technology (HT3) for heavy trucks had the highest potential for synergistic CO_2 and NO_x emission reductions.

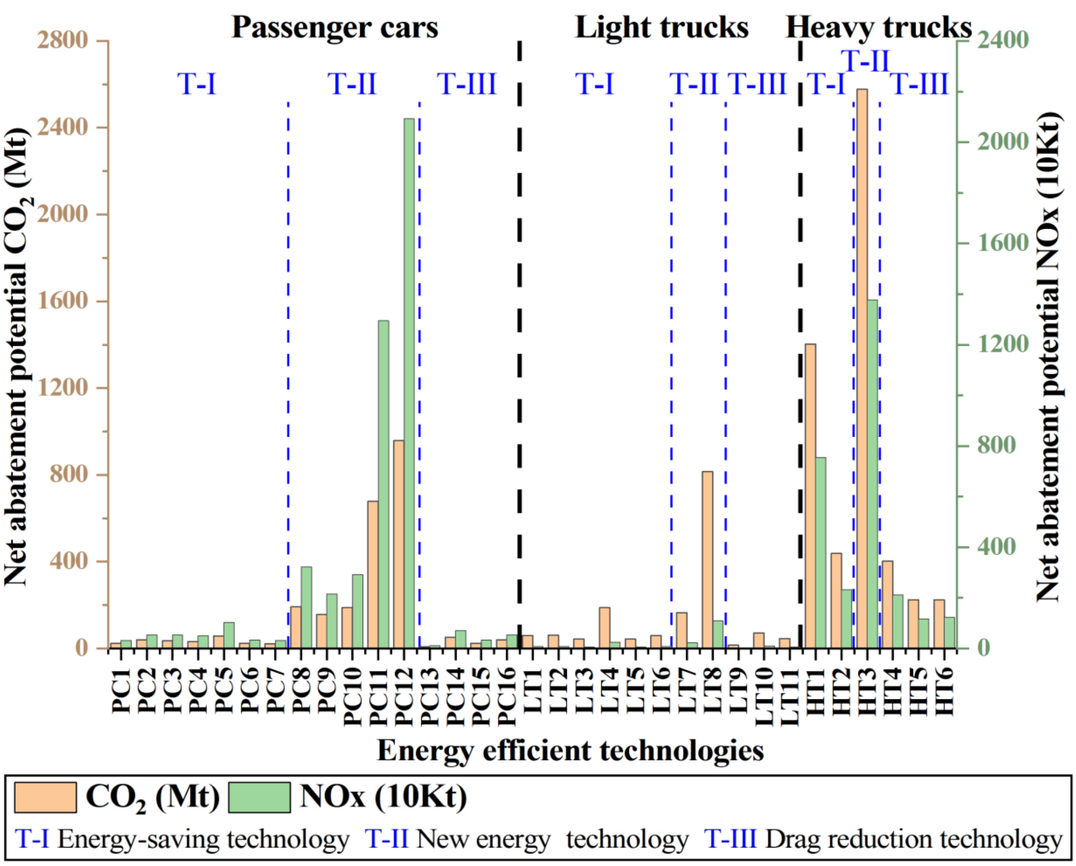

Figure 3. Net abatement potential of 33 specific energy-efficient technologies.

Figure 4 illustrates the net benefits (*NB*) of the 33 energy-efficient technologies, and it can be seen that most technologies are cost-effective. Among all studied technologies, heavy trucks showed the highest net abatement benefits, while passenger cars had the lowest net abatement benefits. In which, new energy technologies (T-II) for passenger cars had the lowest net abatement benefits. On the contrary, new energy technologies for heavy trucks had the highest emission reduction benefits. In addition, the net abatement benefits of engine technologies (T-I) and drag reduction technologies (T-III) were found to be lowest.

The results showed that most of the technologies are able to achieve a net benefit over their life cycle, due to the fact that the economic benefits of fuel savings during the use phase outweigh the investment costs. The net benefits of pure electric technology for passenger cars (PC12) and plug-in hybrid technology for passenger cars (PC11) were negative, meaning that these two technologies do not generate benefits over their life cycle and require some additional expense. PC12 technology had the highest net NO_x abatement potential (20.92 Mt NO_x), with a total net benefit of −1004 billion over its lifetime. Therefore, to implement pure electric vehicles with great emission reduction potential on a large scale, government subsidies would reduce their promotion resistance [49]. In addition, it is worth noting that the parallel hybrid technology for heavy trucks (HT3) had not only the highest CO_2 and NO_x synergistic reduction potential, but also the highest net benefit of all the technologies studied, with a net benefit of 2225 billion yuan, while reducing 2577 Mt CO_2 emissions and 13.76 Mt NO_x emissions. Therefore, HT3 technology is a worthy priority for future emission reduction planning in the road transport sector, both from an economic and environmental point of view.

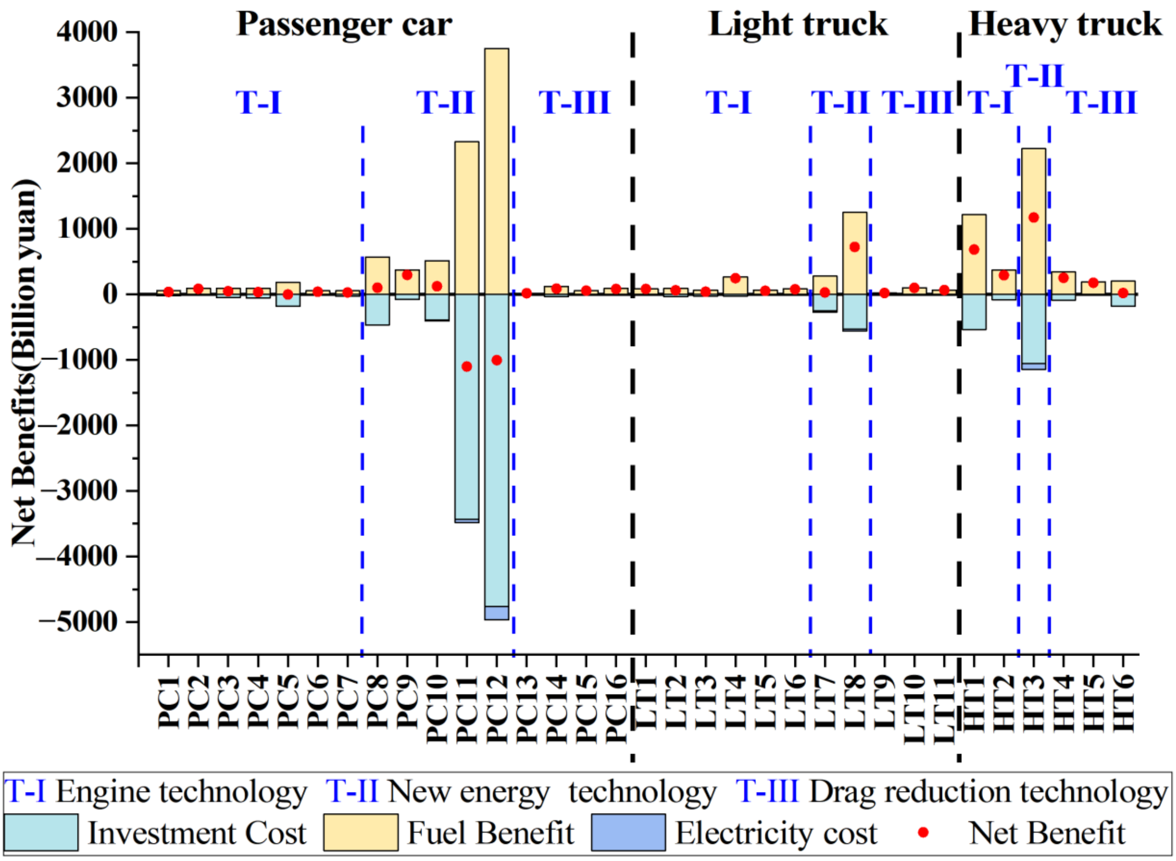

Figure 4. Net benefits of 33 specific energy-efficient technologies.

In sum, there were two main novel findings from the cost–benefit analysis of these technologies. Firstly, we found that, although the pure electric technology for passenger cars (PC12) and the plug-in hybrid technology for passenger cars (PC11) show good huge and synergistic CO_2 and NO_x reduction effects, these technologies also cost the most. Secondly, we found that the parallel hybrid technology (HT3) for heavy trucks not only has huge emission reduction potential, but also requires a relatively low cost compared to PC12 and PC11 technologies. Considering both the net abatement potential and net abatement cost, we believe the parallel hybrid technology for heavy trucks (HT3) is the most desirable abatement pathway to be promoted in the future, as it has a high CO_2 and NO_x synergistic abatement potential and low retrofit cost, which provides the highest economic benefits over the life cycle.

3.3. Uncertainty Analysis

There is some uncertainty in the results of this paper, which mainly comes from two aspects: the reliability of the emission data and the accuracy of the cost and efficiency of abatement technologies.

First of all, the sources of air pollutant emission data for mobile sources in China are generally three influential sources: the environmental statistics yearbook, pollution census data, and annual report of environmental management of mobile sources, but all these three sources only have NO_x data and no CO_2 data. Therefore, in this study, CO_2 emission data were obtained from Tsinghua University CEADs inventory and accounting according to IPCC greenhouse gas guidelines. Of course, due to various factors such as technical level and statistical caliber, there is no absolutely reliable emission inventory for either CO_2 or NO_x. Therefore, although the data collection and measurement methods of CO_2 and NO_x are different, in this study, we used the environmental statistics yearbook [39] and the annual report of mobile source environmental management data [40], published by the Chinese government for NO_x and Tsinghua University CEADs [41] inventory and accounting according to the IPCC greenhouse gas guidelines [42] for CO_2, in order to ensure the accuracy of the data as much as possible.

In the abatement cost analysis section, there is no government published data on the cost and energy saving efficiency of various abatement technologies. Therefore, the data were obtained from the National Science Research Council of America, the National Highway Traffic Safety Administration of America, and related literature. While the research object of this paper is China, there is some uncertainty. Moreover, in this paper, we equate energy saving efficiency with abatement efficiency, but in fact, for the vehicle itself, energy saving efficiency does not necessarily reduce emissions, and may cause an increase in pollutants. The purpose of this study was not to conduct very precise simulations, but to study the chain reaction of the implementation of abatement technologies on the emissions of the whole supply chain, and to propose a new approach to the feasibility analysis of pollution abatement technologies. In the future, more advanced monitoring data may further improve the accuracy of emission inventories, and more research on China's transportation sector may make the cost and abatement capacity of abatement technologies more consistent with the actual situation in China, resulting in less uncertainty in the data.

4. Conclusions

This paper examines the changes in CO_2 and NO_x emissions in the transportation sector and their drivers from 2012–2018, as well as the reduction potential and abatement costs of energy-efficient technologies of the road passenger and road freight transport subsectors. The results showed that CO_2 more than doubled during the study period, from 318 Mt in 2012 to 746 Mt in 2018. Although emissions of NO_x have not increased significantly, its level remains high at 6400 Kt. Current emission reduction measures for transport are weak in terms of CO_2 control. In the coming decades, with the increased demand for the transportation sector, especially the road transport subsector (vehicles), the transportation sector will continue to be a major contributor of CO_2 and NO_x, which are essential for improving air quality. This is consistent with the study by Zhao et al. [50], who found that income and population have a significant impact on vehicle CO_2 emissions. Income and population generate a huge demand for transport. Therefore, China should focus on reducing emissions from the transportation sector, especially from the road subsector, in order to achieve the synergistic pollutant and carbon reduction targets.

This study analyzed the net reduction potential and cost of 33 vehicle energy-efficiency technologies. The results showed that most of the studied technologies showed good synergistic CO_2 and NO_x reduction effects. Moreover, most technologies can deliver benefits with emission reductions. Of all these technologies, new energy technologies have the greatest advantage in net abatement potential, especially pure electric and hybrid technologies. Numerous studies [6,7,50,51] have come to the same conclusion; they are all positive about the abatement potential of new energy technologies. However, in terms of the cost–benefit analysis of this research, new energy technologies are not economically efficient compared to drag reduction technologies and energy-efficient technologies, especially for passenger cars. Specifically, most technologies achieve economic benefits, except for pure electric technology for passenger cars (PC12) and plug-in hybrid technology for passenger cars (PC11), which may require some cost. In addition, the price of oil has a significant impact on whether energy-efficient technologies require costs or return benefits [7,52]. Previously, we used 2010 as the base year, and our results showed that most of the abatement technology options had costs [6]. Whereas in this research, we employed 2018 as the base year, with a fuel price increase of approximately 15% from our previously published study [6], and the results showed that most of the technical options could be profitable. This difference is mainly caused by the increase in fuel prices. We can expect that the economics of new energy technologies for passenger cars using price-stabilized electricity will improve significantly as the price of oil increases [8]. At the same time, both PC12 and PC11 technologies have a high potential for life-cycle emission reductions, despite their high emissions in the production phase. Therefore, gradual electrification is an important path to passenger car emission reduction.

In contrast, new energy technologies for heavy trucks can yield significant benefits, which are considerably more cost-effective than passenger cars. Parallel hybrid technology for heavy trucks (HT3) not only offers the highest CO_2 and NO_x synergistic emission reductions, but also economic benefits over its life cycle. The reason for this situation is that parallel hybrid technology is based on a conventional fuel vehicle, with the modification of twin engines and electronic auxiliaries [53], and therefore, the cost is low compared to replacing the entire vehicle with pure electric technology (PC12). In addition, the parallel hybrid technology for heavy trucks is the technology that can meet the demand of emission reduction and long-distance transportation. At present, parallel hybrid technology for heavy trucks is more common in Europe [54], but it has not been commonly promoted in China. Under the background of China's national strategy of green freight and the optimization of traffic structure, the promotion of hybrid heavy trucks may be a win-win solution for the environment and economy in the near future, compared to the promotion of pure electric technology for passenger cars.

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