

## Article

# Evaluation Method for Nitrogen Oxide Emission Reduction Using Hypothetical Automobile Model: A Case in Guangdong Province

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## Abstract

As a key precursor of tropospheric ozone and secondary particulate matter, nitrogen oxides (NO<sub>x</sub>) exert significant impacts on air quality. Traffic emissions represent a dominant source of near-surface NO<sub>x</sub>. The widespread adoption of new energy vehicles (NEVs) has progressively transformed the automobile fleet composition, leading to measurable reductions in NO<sub>x</sub> emissions. This study developed a NO<sub>x</sub> emission inventory model to quantify the impact of NEV penetration on emission trends in Guangdong (2013–2022), under the assumption that the emission shares of internal combustion engine vehicles (ICEVs) and NEVs have no significant change in adjacent years. Results demonstrate that total vehicular NO<sub>x</sub> emissions peaked in 2019 at  $55.69 \times 10^4$  tons (a 16.6% increase from 2018), followed by a consistent decline. ICEVs exhibited a declining emission share from  $0.037 \times 10^4$  tons/year in 2013 to  $0.022 \times 10^4$  tons/year in 2019—a 40.5% reduction, attributable to progressive technological advancements. Following a marginal increase (2019–2021), the emission share declined significantly to  $0.019 \times 10^4$  tons/year in 2022. In contrast, NEVs contributed to emissions reduction, with maximal mitigation observed in 2021 ( $-0.241 \times 10^4$  tons). ICEVs initially demonstrated emission reductions (2014–2017), succeeded by a transient increase ( $11.7 \times 10^4$  tons through 2021) before resuming decline in 2022. The NEV-driven mitigation effect intensified progressively from 2018 to 2021, with modest attenuation in 2022.

**Keywords:** automobiles; nitrogen oxides; emissions accounting; emission reduction effectiveness



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## 1. Introduction

The nitrogen oxide family (NO<sub>x</sub> = NO + NO<sub>2</sub>), primarily generated through combustion processes—including vehicular emissions, industrial activities, and fossil fuel power plants—also originates from natural sources such as lightning and biomass burning. NO<sub>x</sub> are key components that promote the formation of photochemical smog and precursors of PM<sub>2.5</sub> and tropospheric ozone, which play a crucial role in atmospheric chemistry; they

contribute significantly to environmental challenges like ozone pollution, haze formation, and acid rain [1,2]. Chronic exposure to elevated  $\text{NO}_x$  concentrations is associated with severe health risks, including central nervous system damage, pulmonary edema, bronchial disorders, ocular irritation, and respiratory diseases. Their high toxicity underscores the urgency of emission control measures [3].

Automobile emissions constitute the predominant anthropogenic source of  $\text{NO}_x$  in urban atmospheres. Continuous improvements in internal combustion engine (ICE) technology and exhaust aftertreatment systems have progressively reduced  $\text{NO}_x$  emissions from ICE vehicle (ICEVs). Current mitigation strategies focus primarily on two approaches: optimizing engine combustion efficiency and implementing advanced exhaust filtration systems that incorporate catalytic converters and particulate filters [4]. Wang et al. [5] indicated that emissions at load rates below 30% during LLCs account for more than 67.5% of the total cycle emissions, particularly under idling and start–stop conditions. Vijai et al. [6] reported that exhaust gas recirculation (EGR) set at 15–25% resulted in the best emission control in Low-Temperature Combustion (LTC) engines. In contrast to ICEV, new energy vehicles (NEVs) utilize battery-powered propulsion systems, thereby eliminating direct  $\text{NO}_x$  emissions from fuel combustion during operation [7]. The widespread adoption of NEVs offers dual environmental benefits: reducing ICEV emissions while significantly contributing to greenhouse gas mitigation. Projections indicate that achieving carbon neutrality in road transport by 2060 through NEV deployment could reduce cumulative greenhouse gas emissions by 48%, compared to 2020–2060 baseline scenarios [3]. Life cycle assessment using the Well-to-Wheels (WTW) methodology demonstrates substantially lower carbon emissions and reduced energy consumption for NEVs [8]. Furthermore, studies have identified significant co-benefits for air quality improvement, with NEVs showing marked reductions in multiple atmospheric pollutants ( $\text{NO}_x$ , CO, NMHC,  $\text{SO}_2$ , and  $\text{PM}_{10}$ ) and  $\text{CO}_2$  when replacing ICEVs [9]. The promotion of NEVs shows great potential for emission reduction.

The Chinese government has successively implemented supportive policies to promote the development of NEV industries. The *Development Plan for New Energy Vehicle Industries (2021–2035)* sets a target to significantly enhance the market competitiveness of NEVs by 2025. Regarding  $\text{NO}_x$  emission control, China has established specific emission standards for six major industries, including thermal power, ironmaking, steel, cement, brick production, and boilers. Since 2015, the national ultra-low-emission standards have been progressively implemented for coal-fired power plants and steel industries. The Ministry of Ecology and Environment has formulated and issued one ambient air quality standard, one comprehensive standard, and eight industry-specific emission standards [10]. Guangdong Province, as a major market for new energy technologies, has actively supported NEV and renewable energy development through its *14th Five-Year Plan*, and it serves as an ideal research area for investigating the  $\text{NO}_x$  reduction effects resulting from rapid NEV adoption [10]. Quantifying the specific impacts of automobile fleet structure changes on  $\text{NO}_x$  reduction provides crucial scientific references for pollution control measures and atmospheric environment improvement, while informing future policy optimization [11].

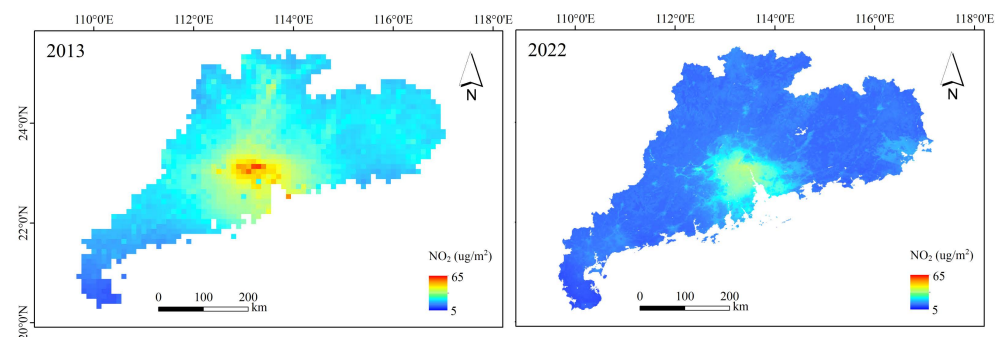
Many researchers have attempted to optimize models or upgrade configurations to explore the effectiveness of nitrogen oxide emission reduction. Zhou et al. [12] demonstrated how machine learning can model nonlinear relationships in emission processes, which is a methodology transferable to vehicle emission prediction where similar nonlinear dynamics exist between engine parameters and  $\text{NO}_x$  output. Simpkins pointed out the potential of electric vehicles (EVs) as a critical pathway for nitrogen oxide ( $\text{NO}_x$ ) mitigation [13]. Feng et al. [14] comprehensively depicted global sectoral human-induced nitrous oxide ( $\text{N}_2\text{O}$ ) emissions by country, previewed the economic costs and social benefits from abating  $\text{N}_2\text{O}$

emissions, and summarized roadblocks for achieving  $\text{N}_2\text{O}$  emission reductions. Amin et al. discussed technologies for controlling  $\text{NO}_x$  emissions from vehicular engines, such as exhaust gas recirculation and selective catalytic reduction, providing engine-level control techniques for internal combustion engine vehicles (ICEVs) [15]. Akopov et al. [16] simulated dynamic interactions between pollutants and urban ecosystems with an agent-based modeling framework. While the case focuses on stationary sources, its methodology provides valuable insights into simulating complex system-level interactions between emission sources and environmental factors. Current research reveals a vacancy in evaluating  $\text{NO}_x$  reduction effects associated with NEV-induced transformations in automobile fleet structures. This study develops a multi-source data-driven  $\text{NO}_x$  emission accounting model to quantify emission shares from both ICEVs and NEVs. Focusing on Guangdong Province as a demonstration area, we systematically assess the absolute reduction and proportional contributions of  $\text{NO}_x$  emissions from these two automobile types during 2013–2022, thereby evaluating the  $\text{NO}_x$  reduction effectiveness resulting from structural changes in the automobile industry. The rest of the paper is organized as follows: Section 2 presents the data and methods. Section 3 presents the results and discussion. Section 4 provide some conclusions and policy recommendations.

## 2. Data and Methods

### 2.1. General Situation

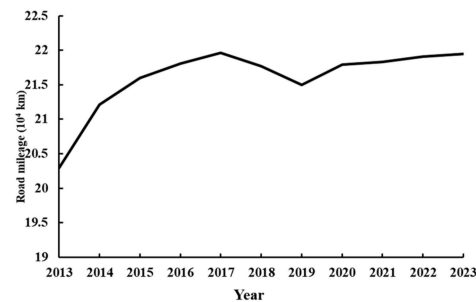
The near-surface  $\text{NO}_2$  concentration data obtained from the National Earth System Science Data Sharing Platform—Yangtze River Delta Science Data Center (<http://geodata.nnu.edu.cn>, accessed on 10 March 2025) [17] reveal a general declining trend in  $\text{NO}_2$  concentrations across Guangdong Province from 2013 to 2022. The provincial  $\text{NO}_2$  levels in 2022 were significantly lower than those recorded in 2013 (Figure 1) [18].



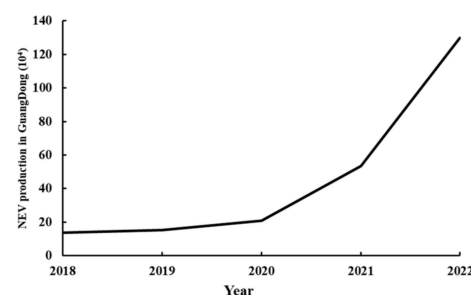
**Figure 1.** Spatial patterns of  $\text{NO}_2$  in Guangdong Province in 2013 ((left), spatial resolution of 10 km) and 2022 ((right), spatial resolution of 1 km).

As of 2023, Guangdong Province had registered a total of  $4174 \times 10^4$  automobiles. Figure 2 demonstrates the continuous expansion of road mileage in the province, indicating relatively high vehicular activity levels. As a key hub for the NEV industry in China, Guangdong has achieved remarkable progress in NEV development in recent years. According to the *China Automobile Environmental Management Annual Report*, NEV production in Guangdong shows consistent annual growth, with the most significant increase occurring between 2021 and 2022 (Figure 3). During the 13th Five-Year Plan period, Guangdong implemented vigorous measures to reduce automobile emissions. The provincial government issued the *Implementation Opinions on Accelerating the Promotion and Application of New Energy Vehicles*, which effectively boosted NEV adoption. By 2020, the electrification rate of public buses reached 97.5%, accompanied by a 27.6% growth in NEV production [19–21]. This growth momentum continued, with NEV production reaching 2.5318 million units

in 2023, accounting for 26.8% of total NEV output. These developments underscore the crucial role of NEVs in reducing pollutant emissions [22].



**Figure 2.** Evolution of highway mileage in Guangdong Province.



**Figure 3.** Production of NEVs in Guangdong Province from 2018 to 2023.

## 2.2. Data Introduction

### 2.2.1. Number of ICEVs in Guangdong Province

According to the data released by *the China Statistical Yearbook* from 2014 to 2013, the number of various types of ICEVs in Guangdong Province during the past decade was obtained (Table 1).

**Table 1.** Number of various types of ICEVs in Guangdong Province (10<sup>4</sup>).

| Year/Type | Large Freight | Medium Freight | Light Freight | Mini Freight | Large Passenger | Medium Passenger | Compact Passenger | Mini Passenger |
|-----------|---------------|----------------|---------------|--------------|-----------------|------------------|-------------------|----------------|
| 2013      | 23.2          | 17.74          | 134.57        | 3.38         | 15.62           | 16.88            | 947.69            | 12.21          |
| 2014      | 25.83         | 15.83          | 136.69        | 3.49         | 15.41           | 13.58            | 1103.63           | 11.56          |
| 2015      | 26.36         | 12.9           | 132.2         | 3.44         | 15.31           | 8.72             | 1256.25           | 10.3           |
| 2016      | 29.09         | 12.45          | 138.58        | 2.90         | 16.3            | 7.44             | 1453.45           | 8.46           |
| 2017      | 33.25         | 11.81          | 148.49        | 2.45         | 17.47           | 6.49             | 1660.09           | 7.91           |
| 2018      | 37.71         | 11.46          | 166.45        | 2.29         | 17.67           | 5.66             | 1860.01           | 7.96           |
| 2019      | 42.4          | 11.13          | 181.95        | 2.03         | 17.51           | 5.14             | 2050.77           | 7.55           |
| 2020      | 49.36         | 10.78          | 197.63        | 1.72         | 16.64           | 4.67             | 2203.72           | 6.93           |
| 2021      | 56.56         | 10.13          | 213.75        | 1.31         | 15.72           | 4.37             | 2384.04           | 6.34           |
| 2022      | 55.37         | 9.13           | 219.67        | 0.88         | 14.63           | 3.96             | 2576.32           | 5.65           |

### 2.2.2. Number of NEVs in Guangdong Province from 2018 to 2022

According to *the annual reports on mobile source environment management* and *China's new energy automobile industry*, data on national NEV ownership and production, as well as NEV production in Guangdong Province from 2018 to 2022, were obtained (Table 2).

**Table 2.** NEV ownership and production from 2018 to 2022 ( $10^4$ ).

| Year | National NEV In-Use Stock | National NEV Output | Guangzhou NEV Output |
|------|---------------------------|---------------------|----------------------|
| 2018 | 261                       | 127                 | 13.67                |
| 2019 | 381                       | 124.2               | 15.26                |
| 2020 | 492                       | 136.6               | 20.87                |
| 2021 | 784                       | 354.5               | 53.5                 |
| 2022 | 1310                      | 705.8               | 129.73               |

### 2.3. Method

#### 2.3.1. Calculation of Number of NEVs in Guangdong Province

The number of NEVs in Guangdong Province was calculated according to Equation (1):

$$NEV\_num = \frac{NEV\_yield_{GD}}{NEV\_yield_{ALL}} \times NEV_{ALL} \quad (1)$$

In this equation,  $NEV\_num$  represents the number of NEVs in Guangdong Province,  $NEV\_yield_{GD}$  represents the production of new energy automobiles in Guangdong Province, and  $NEV\_yield_{ALL}$  represents the national production of new energy automobiles.

#### 2.3.2. Calculation of $NO_x$ Emissions from Automobiles in Guangdong Province

The  $NO_x$  emissions of automobiles in Guangdong Province are calculated using Equation (2):

$$NO_{x\_emission_{GD}} = \frac{automobile\_hold_{GD}}{automobile\_hold_{ALL}} \times NO_{x\_emission_{ALL}} \quad (2)$$

In this equation,  $NO_{x\_emission_{GD}}$  represents the nitrogen oxide emissions of automobiles in Guangzhou,  $NO_{x\_emission_{ALL}}$  represents the nitrogen oxide emissions of automobiles in China,  $automobile\_hold_{GD}$  represents the number of automobiles in Guangzhou, and  $automobile\_hold_{ALL}$  represents the number of automobiles in China.

#### 2.3.3. Accounting Model for $NO_x$ Emission from ICEVs and NEVs

This study establishes a  $NO_x$  emission accounting model for both ICEVs and NEVs, operating under two fundamental assumptions:

(I) Hypothetical automobile equivalents are defined (representing compact or sub-compact automobiles for both automobile types) to enable emission quantification based on numerical shares. This approach permits substitution of actual automobile types with their hypothetical equivalents. The  $NO_x$  emission shares for ICEV and NEV hypothetical automobiles are denoted as  $p_1$  and  $p_2$ , respectively. A positive emission share ( $p_i > 0$ ) indicates  $NO_x$  emission contribution, while a negative value ( $p_i < 0$ ) signifies  $NO_x$  reduction contribution. These assumptions necessitate establishing conversion factors between actual automobile emissions and their hypothetical equivalents.

Per-kilometer fuel consumption for different ICEV types is derived from published studies on operational truck/passenger automobile fuel consumption patterns, small internal combustion engine technologies, and China Corporate Average Fuel Consumption (CAFC) standards with associated limits [23–26]. These data provide the foundation for calculating fuel mass consumption rates across automobile classifications.

Considering the emission share of micro and small cargo automobiles as  $p_1$ , the emission share coefficient  $n$  of other types of ICEV was calculated by the mass ratio of fuel consumption per kilometer, referring to Table 3 [27,28]. Equation (3) is as follows:

$$n \times p_1 = \frac{d}{0.056} \quad (3)$$

where  $n$  is the emission share coefficient of automobiles,  $p_1$  is the emission share of micro and small cargo automobiles (Hypothetical automobile), and  $d$  is the consumption per kilometer of automobiles.

**Table 3.** Mass-specific fuel consumption (g/km) by ICEV category.

| Year            | Automobile Stock<br>b (10 <sup>4</sup> ) | Travel Distance c<br>(10 <sup>4</sup> km) | Fuel Consumption<br>d (kg/km) |
|-----------------|------------------------------------------|-------------------------------------------|-------------------------------|
| Mini/compact    | 2390.3                                   | 1.8                                       | 0.056                         |
| Medium          | 4.36                                     | 3.13                                      | 0.163                         |
| Large           | 8.94                                     | 5.8                                       | 0.163                         |
| Taxi            | 5.41                                     | 12                                        | /                             |
| Mini/light-duty | 213.77                                   | 3                                         | 0.105                         |
| Medium-duty     | 10.13                                    | 3.5                                       | 0.157                         |
| Heavy-duty      | 56.56                                    | 7.5                                       | 0.252                         |

We obtained the emission shares of large trucks, medium trucks, small and micro trucks, large buses, and medium buses as  $4.5 p_1$ ,  $2.803 p_1$ ,  $1.875 p_1$ ,  $2.91 p_1$ , and  $2.91 p_1$ , respectively. The coefficient was multiplied by the number of corresponding types of automobiles in each year to obtain a relatively accurate result.

(II) Assuming that there are no major breakthroughs in technological innovations such as internal combustion engines and electric motors between adjacent years, the hypothetical  $\text{NO}_x$  emission shares  $p_1$  and  $p_2$  of ICEVs and NEVs remain basically unchanged between adjacent years.

$\text{NO}_x$  emission shares  $p_1$  and  $p_2$  were calculated using Equation (4):

$$\begin{cases} I_1 \times p_1 + N_1 \times p_2 = \text{NO}_x\text{emission}_n \\ I_2 \times p_1 + N_2 \times p_2 = \text{NO}_x\text{emission}_{n+1} \end{cases} \quad (4)$$

In this equation,  $I_1$ ,  $N_1$ ,  $p_1$ , and  $\text{NO}_x\text{emission}_n$  are the number of ICEVs, the number of NEVs, the share of  $\text{NO}_x$  emissions, and the amount of  $\text{NO}_x$  emissions in the  $n$ th year, respectively.  $I_2$ ,  $N_2$ ,  $p_2$ , and  $\text{NO}_x\text{emission}_{n+1}$  are the number of ICEVs, the number of NEVs, the share of  $\text{NO}_x$  emissions, and the amount of  $\text{NO}_x$  emissions in the  $(n + 1)$ th year, respectively.

#### 2.3.4. Proportion of Emission Reductions for ICEVs and NEVs

By calculating  $p_1$  and  $p_2$  from the previous step and combining them with the number of ICEVs and NEVs in that year, the  $\text{NO}_x$  emissions reductions of ICEVs and NEVs in that year were multiplied. Compared with the total emission reductions in that year, the proportion of emission reductions of ICEVs and NEVs to the total emission reductions was obtained. The formula is Equation (5):

$$\begin{cases} \text{Ratio}_{\text{ICEV}} = \frac{I_2 \times p_1 - I_1 \times p_1'}{\text{NO}_x\text{reduction}_{\text{total}}} \\ \text{Ratio}_{\text{NEV}} = \frac{N_2 \times p_2 - N_1 \times p_2'}{\text{NO}_x\text{reduction}_{\text{total}}} \end{cases} \quad (5)$$

In this equation,  $NO_x\_reduction_{total}$  represents the emission reduction during a certain two-year period;  $I_1$ ,  $N_1$ ,  $p_1'$ , and  $p_2'$  are the quantities of ICEVs and NEVs in the  $(n - 1)$ th year, respectively;  $I_2$ ,  $N_2$ ,  $p_1$ , and  $p_2$  are the number of ICEVs, the number of NEVs, the share of nitrogen oxide emissions from ICEVs, and the share of  $NO_x$  emissions from NEVs in the  $n$ th year.

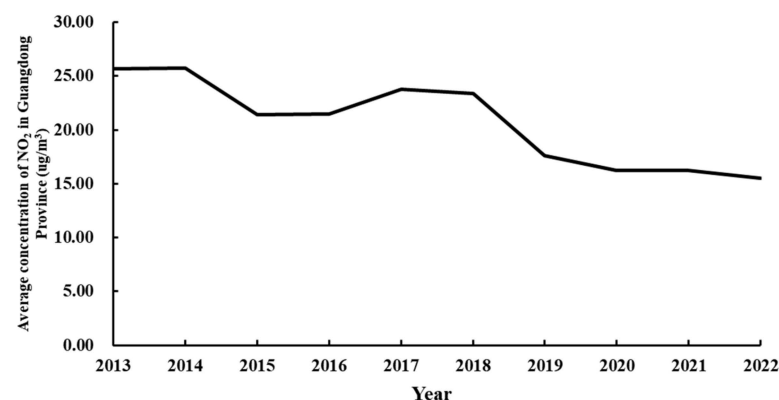
### 3. Results and Discussion

#### 3.1. Annual Variation in Near-Surface $NO_2$ in Guangdong Province

The statistical analysis of near-surface  $NO_2$  concentration data in Guangdong Province from 2013 to 2022 reveals distinct temporal trends. As shown in Table 4 and Figure 4, the annual average  $NO_2$  concentrations exhibited a continuous decline from 2013 to 2015. The 2015 average concentration of  $21.44 \mu\text{g}/\text{m}^3$  represented a 16.4% reduction compared to 2013 levels. However, a moderate rebound occurred between 2016 and 2018, with the 2018 concentration increasing by approximately 8.9% relative to 2015. The most significant decrease was observed from 2018 to 2019, when  $NO_2$  levels dropped sharply by 24.6%. Following this rapid decline, the decreasing trend was moderated, with a further 12.1% reduction from 2019 to 2022 [29–32]. The interannual variation demonstrates an overall downward trend in provincial  $NO_2$  concentrations throughout the 2013–2022 period. This consistent reduction in average concentrations has correspondingly led to a progressive decrease in total nitrogen oxide emissions [24].

**Table 4.** Annual average concentration of  $NO_2$  in Guangdong Province from 2013 to 2022.

| Year | $NO_2$ Concentration ( $\mu\text{g}/\text{m}^3$ ) |
|------|---------------------------------------------------|
| 2013 | 25.689                                            |
| 2014 | 25.714                                            |
| 2015 | 21.437                                            |
| 2016 | 21.474                                            |
| 2017 | 23.753                                            |
| 2018 | 23.368                                            |
| 2019 | 17.624                                            |
| 2020 | 16.239                                            |
| 2021 | 16.239                                            |
| 2022 | 15.487                                            |



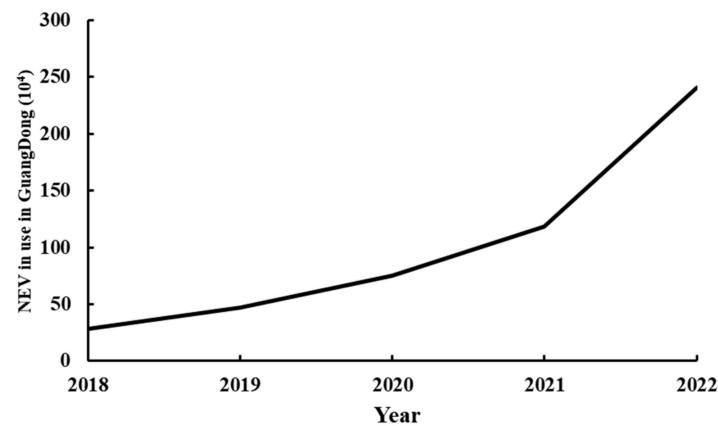
**Figure 4.** Near-surface  $NO_2$  concentration of Guangdong Province from 2013 to 2022.

#### 3.2. Accounting for $NO_x$ Automobile Emissions in Guangdong Province

##### 3.2.1. The Number of NEVs in Guangdong Province from 2018 to 2022

Analysis of automobile registration data (Figure 5) in Guangdong Province over the past decade (2012–2022) reveals a consistent upward trend in total automobile ownership.

Among all automobile categories, light passenger automobiles accounted for both the largest share and the most significant annual growth. Based on collected statistics and calculations using Equation (1), the registered NEV population in Guangdong increased from 280,900 units in 2018 to 1.183 million units in 2021. The most dramatic growth occurred between 2021 and 2022, when the NEV fleet expanded by 103.55% to reach 2.408 million units.



**Figure 5.** The number of NEVs in Guangdong Province from 2018 to 2022.

### 3.2.2. NO<sub>x</sub> Emissions from Automobiles in Guangdong Province from 2013 to 2022

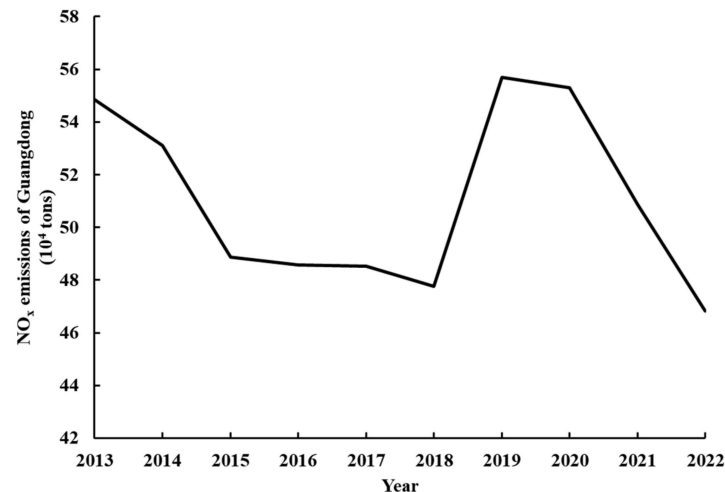
Based on the statistical data released in *the annual report on mobile source environmental management*, the nitrogen oxide emissions in Guangdong Province were calculated using Equation (2), and the results are shown in Table 5.

**Table 5.** NO<sub>x</sub> emissions in Guangdong Province during the past decade.

| Year | National Automobile Stock (10 <sup>4</sup> ) | Guangdong Automobile Stock (10 <sup>4</sup> ) | National NO <sub>x</sub> Emissions (10 <sup>4</sup> tons) | Guangdong NO <sub>x</sub> Emissions (10 <sup>4</sup> tons) |
|------|----------------------------------------------|-----------------------------------------------|-----------------------------------------------------------|------------------------------------------------------------|
| 2013 | 12,572.4                                     | 1171.3                                        | 588.7                                                     | 54.84587748                                                |
| 2014 | 14,452.2                                     | 1326                                          | 578.9                                                     | 53.1145016                                                 |
| 2015 | 16,169.7                                     | 1465.5                                        | 539.1                                                     | 48.85996957                                                |
| 2016 | 18,435.8                                     | 1675.5                                        | 534.6                                                     | 48.58602827                                                |
| 2017 | 20,816                                       | 1896                                          | 532.8                                                     | 48.52943889                                                |
| 2018 | 23,121.8                                     | 2116                                          | 521.9                                                     | 47.76186975                                                |
| 2019 | 26,000                                       | 2326.95                                       | 622.2                                                     | 55.68570346                                                |
| 2020 | 28,100                                       | 2532.29                                       | 613.7                                                     | 55.30485313                                                |
| 2021 | 30,200                                       | 2702                                          | 568.5                                                     | 50.86380795                                                |
| 2022 | 31,900                                       | 2896                                          | 515.9                                                     | 46.83531034                                                |

Analysis of the data presented in Table 5 and Figure 6 reveals distinct trends in NO<sub>x</sub> emissions in Guangdong Province from 2013 to 2022. In 2013, total automotive NO<sub>x</sub> emissions reached 548.5 thousand tons, followed by a gradual decline to 477.6 thousand tons by 2018—representing a 12.93% reduction over this five-year period. However, a notable emission rise occurred in 2019, with NO<sub>x</sub> levels rising to 556.9 thousand tons (a 16.6% increase compared to 2018), marking the peak emission year during the study period. Subsequently, emissions demonstrated a consistent year-on-year decrease. The Annual Report on Mobile Source Environmental Management in China confirms a transient increase in NO<sub>x</sub> emissions from the automotive sector in 2019. It is hypothesized that this may be attributable to a policy-driven surge in pre-compliance vehicle sales. As the phased implementation of the China 6 emission standards approached, manufacturers accelerated sales of China

5-compliant light-duty vehicles (LDVs) to clear inventory. Consistent with this hypothesis, annual report data reveal a substantial spike in China 5 LDV registrations during the first half of 2019, which likely contributed to elevated fleet-average NO<sub>x</sub> emissions. The overall decade-long trend shows a net reduction in vehicular NO<sub>x</sub> emissions. Prior to 2018, when NEV adoption remained limited, ICEVs dominated emission contributions. The post-2019 emission reductions correlate strongly with accelerated NEV market penetration in Guangdong Province.



**Figure 6.** NO<sub>x</sub> emissions in Guangdong Province from 2013 to 2022.

These findings establish a clear temporal association between expanding NEV market share (particularly after 2018) and declining NO<sub>x</sub> emissions. This study therefore quantitatively evaluates the relative contributions of ICEVs and NEVs to NO<sub>x</sub> emission reductions, with particular focus on determining their respective proportional impacts.

### 3.3. Evaluation of Emission Reduction Effectiveness of NEVs and ICEVs

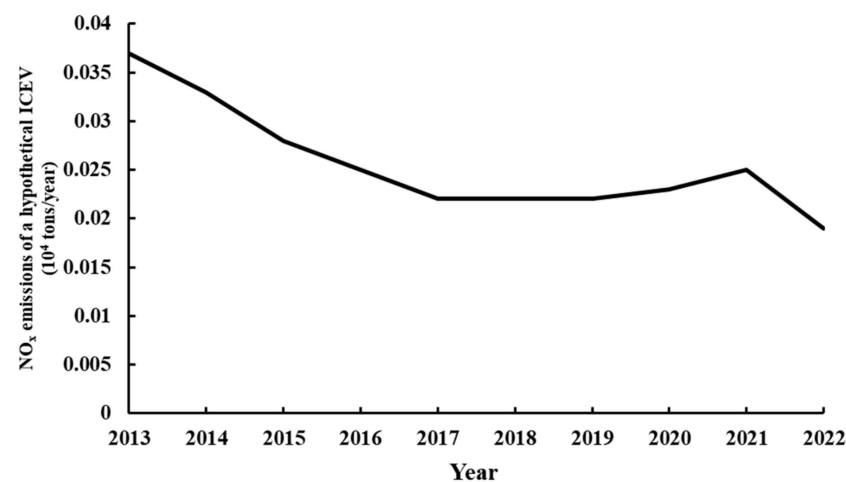
#### 3.3.1. Accounting for the Share of NO<sub>x</sub> Emissions from NEVs and ICEVs

Through iterative validation of the NO<sub>x</sub> emission accounting model, we obtained the annual values of the parameters  $p_1$  and  $p_2$ . The close proximity of  $p_1$  between adjacent years proves the validity of hypothesis II. The negative  $p_2$  represents the contribution of NEVs to reducing emissions, which is in line with the key differences in combustion products between new energy technology and internal combustion engine technology. As presented in Table 6 and Figure 7, the  $p_1$  values (representing conventional automobiles) exhibited a general declining trend from 2013 to 2019. The emission share peaked at 0.037 thousand tons/year in 2013 and decreased to 0.022 thousand tons/year by 2019, representing a 40.5% reduction. Between 2019 and 2021, the emission share showed a slight increase, followed by a notable decline to 0.019 thousand tons/year in 2022—a 17.4% decrease compared to 2020 levels. We simulated and calculated the confidence intervals (Table 6) for the direct outputs ( $p_1$  and  $p_2$ ) of the model using Monte Carlo simulations with 1000 iterations, assuming that activity levels and emission factors follow a log-normal distribution [33]. The 95% confidence intervals for  $p_1$  are (0.0254, 0.0261) and  $p_2$  are (−0.169, −0.157).

Consistent reduction in per-automobile NO<sub>x</sub> emissions from ICEVs demonstrates the effectiveness of continuous engine upgrades and improved exhaust filtration systems implemented over the past decade. The findings suggest substantial remaining potential for conventional automobiles to further reduce NO<sub>x</sub> emissions, highlighting their continued importance in regional emission mitigation strategies [26,29].

**Table 6.** Results of  $p_1$  and  $p_2$  from 2013 to 2022.

| Year                       | $p_1$ ( $10^4$ tons/Year) | $p_2$ ( $10^4$ tons/Year) |
|----------------------------|---------------------------|---------------------------|
| 2013                       | 0.037                     | /                         |
| 2014                       | 0.033                     | /                         |
| 2015                       | 0.028                     | /                         |
| 2016                       | 0.025                     | /                         |
| 2017                       | 0.022                     | /                         |
| 2018                       | 0.022                     | −0.222                    |
| 2019                       | 0.022                     | −0.10                     |
| 2020                       | 0.023                     | −0.18                     |
| 2021                       | 0.025                     | −0.241                    |
| 2022                       | 0.019                     | −0.074                    |
| Simulated Logarithmic Mean | 0.026                     | −0.163                    |
| 95% Confidence Interval    | (0.0254, 0.0261)          | (−0.169, −0.157)          |

**Figure 7.** Emissions shares of ICEVs in various years.

As presented in Table 6 and Figure 8, the emission share parameter for NEVs exhibits fluctuating yet consistently negative values ( $-0.001$  to  $-0.241 \times 10^4$  tons/year), quantitatively demonstrating their NO<sub>x</sub> reduction contribution. The maximum reduction reached  $-2410$  tons/year (equivalent to  $-0.241 \times 10^4$  tons/year) in 2021, representing the most effective annual mitigation performance. Although NEVs emerged later than conventional automobiles, they achieved substantial market penetration post-2018. The persistent negative emission shares align fundamentally with near-zero direct NO<sub>x</sub> emissions of NEVs. These results confirm that NEVs contribute significantly to NO<sub>x</sub> reduction, establishing NEVs as one of the primary drivers of transportation sector NO<sub>x</sub> mitigation since 2018 [15,34]. One reason for the decline in the impact of NEVs after 2021 may be that people have been keen on returning to their distant hometowns or traveling after COVID-19, and ICEVs are usually more suitable for long-distance travel, while another possibility is that the NEV market is gradually becoming saturated.

Figure 9 shows a comparison of NO<sub>x</sub> emissions from our hypothetical automobile model and NO<sub>x</sub> emissions calculated with Equation (2) using data from *the annual report on mobile source environmental management*, with correlation coefficient  $R^2$  reaching 0.7015, indicating that both exhibit consistent emission estimates overall. We likewise employed the Monte Carlo method to conduct 1000 simulations of NO<sub>x</sub> emissions from ICEVs and NEVs derived from the hypothetical automobile model, assessing the uncertainty in the

computational results. The obtained 95% confidence intervals were (48.468, 49.528) for ICEVs and (−16.43, −14.626) for NEVs. Critically, it is essential to note that growth trajectories are not perpetually sustainable for ICEVs or NEVs; a gradual saturation trend is anticipated. Consequently, when calculating the emission shares attributable to ICEVs and NEVs, the hypothetical automobile model must incorporate uncertainties associated with key data from countries and regions, which include vehicle fleet size, total NO<sub>x</sub> emissions, and fuel consumption per kilometer.

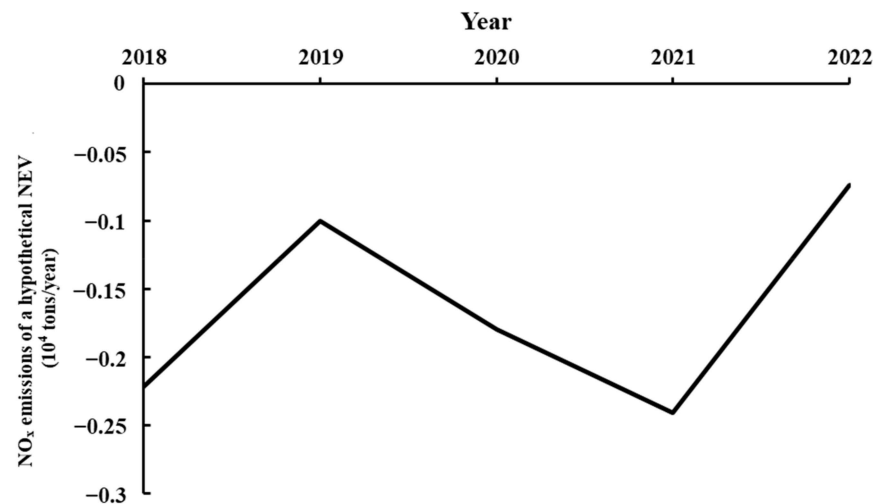


Figure 8. Emission shares of NEVs in various years.

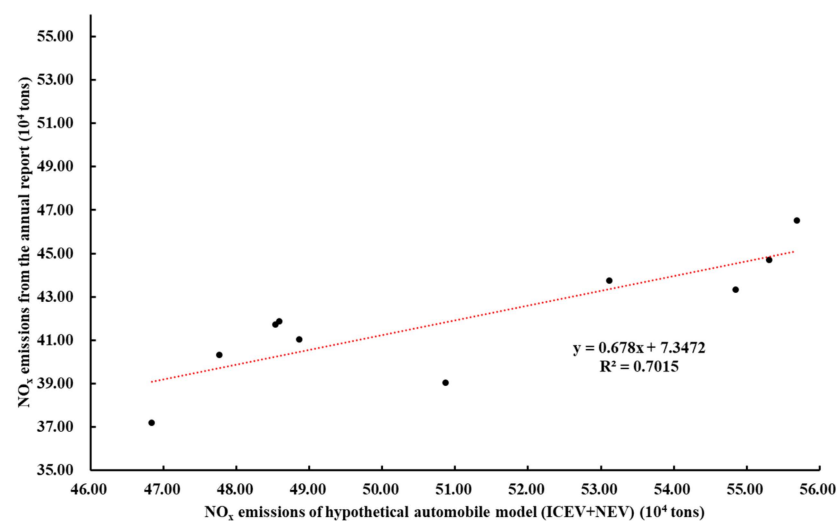


Figure 9. Comparison of NO<sub>x</sub> emissions from hypothetical automobile model and NO<sub>x</sub> emissions calculated with Equation (2) using data from the annual report on mobile source environmental management.

### 3.3.2. Calculation of the Proportion of Emission Reduction Between NEVs and ICEVs

Quantitative assessment of emission reductions through formalized calculations reveals distinct temporal patterns in mitigation contributions from NEVs and ICEVs. As illustrated in Figures 10 and 11, ICEVs demonstrated positive reduction effects during 2014–2017, though the magnitude decreased annually. Conversely, this automobile category exhibited emission increases from 2017 to 2021, peaking at  $11.7 \times 10^4$  tons in 2021, before returning to reduction status in 2022. Prior to 2020, conventional automobiles contributed minimally to provincial emission reductions, with relatively stable proportional contributions. Post-2020, their proportional contribution increased substantially. Meanwhile, NEVs

displayed oscillatory mitigation patterns during 2018–2022. The mitigation effect strengthened progressively from 2018 to 2021, followed by a moderate decline in 2022 relative to 2021 levels. The proportional contribution of NEVs to provincial reductions remained comparatively low during 2018–2020, surged to its maximum in 2021, and experienced a slight decrease in 2022 relative to the previous year [35,36].

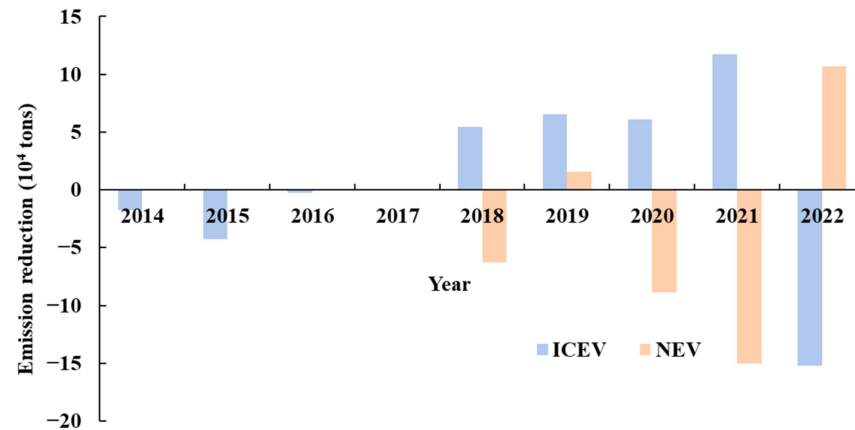


Figure 10. Emission reduction of NEVs and ICEVs in Guangdong Province from 2014 to 2022.

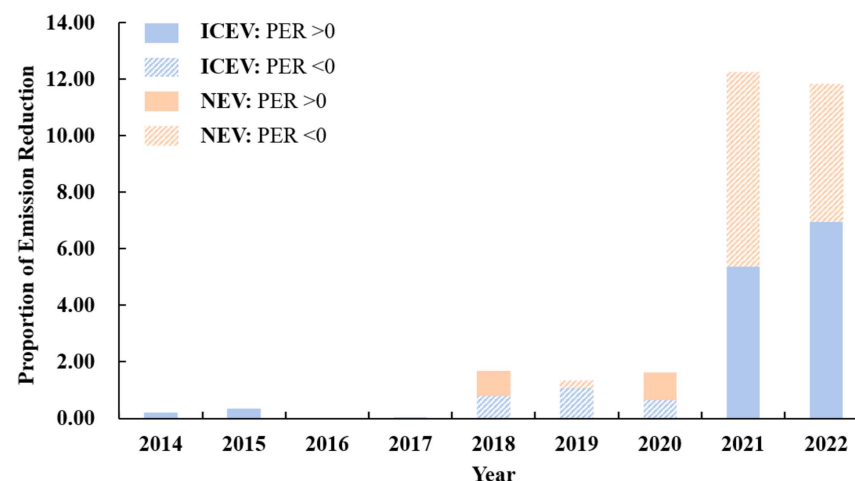


Figure 11. Proportion of emission reduction (PER) of NEVs and ICEVs in Guangdong Province from 2014 to 2022.

## 4. Conclusions and Policy Recommendations

### 4.1. Conclusions

This study quantifies the NO<sub>x</sub> mitigation effectiveness resulting from NEV adoption in Guangdong Province (2013–2022) through a novel NO<sub>x</sub> emission accounting framework.

Analysis reveals a consistent downward trajectory in annual mean NO<sub>2</sub> concentrations during 2013–2015. The 2015 concentration (21.44 µg/m<sup>3</sup>) represented a 16.4% reduction relative to 2013 levels. Subsequently, a moderate rebound occurred (2016–2018), culminating in an 8.9% elevation compared to 2015. A sharp 24.6% decline followed during 2018–2019, transitioning to a gradual 12.1% reduction from 2019 to 2022, collectively demonstrating substantial atmospheric improvement.

ICEVs exhibited a declining emission share from  $0.037 \times 10^4$  tons/year in 2013 to  $0.022 \times 10^4$  tons/year in 2019, a 40.5% reduction, with maximum mitigation efficacy observed during 2017–2019. Following a marginal increase (2019–2021), the emission share declined significantly to  $0.019 \times 10^4$  tons/year in 2022, equivalent to a 17.4% decrease

from 2020. NEVs demonstrated consistent negative emission shares with an oscillatory upward trajectory, confirming their growing mitigation capacity. The peak reduction magnitude reached  $-0.241 \times 10^4$  tons/year in 2021, reflecting maximum annual mitigation performance [32,37].

Prior to 2018, when NEVs had limited market penetration, ICEVs dominated NO<sub>x</sub> reduction efforts. During 2014–2017, ICEVs achieved positive emission reductions, though the magnitude decreased annually. This trend reversed during 2017–2021, with net emissions increasing by  $11.7 \times 10^4$  tons by 2021. Concurrently, NEVs showed progressively stronger mitigation effects from 2018 to 2021, though 2022 saw a moderate decline compared to 2021. Proportional NEV contribution to provincial reductions remained relatively low during 2018–2020, peaked in 2021, and then experienced a slight decrease in 2022.

While NEVs demonstrate significant contributions to NO<sub>x</sub> reduction [38,39], ICEVs retain substantial potential for further emission reductions. This underscores the critical importance of transitioning the automobile fleet of Guangdong Province toward cleaner, more sustainable technologies [7,37,40–43].

#### 4.2. Policy Recommendations

(I) Energy conservation and emission reduction require strong government–enterprise collaboration. Assessing the NO<sub>x</sub> emissions from Guangdong’s motor automobile industry structure provides a valuable window to evaluate emission reduction potential. The government should fully leverage its guiding role to promote increased corporate investment in advanced fuel technologies, exhaust treatment systems, and other related areas; intensify industrial renewal and technological investment efforts; and accelerate relevant industries’ low-carbon transformation.

(II) NEVs significantly contribute to NO<sub>x</sub> emission reduction. Therefore, the vigorous promotion of NEVs should be continued, as this is a key pathway for promoting green development in the transportation sector [44,45]. Simultaneously, supporting the retirement of outdated or non-compliant ICEVs is essential to fully realize the emission reduction potential of the existing ICEV fleet [44–50].

(III) There is a need for policy-driven clean energy transition and continuously deepened demand-side reform. Continuously optimize and implement consumer-oriented NEV purchase and usage subsidy policies and promote the development of hybrid energy automobiles. Prioritize strengthening the infrastructure layout, such as the planning, layout, and construction investment in public charging piles and fast-charging networks. Mobilize the enthusiasm of social capital participation through market incentive measures (e.g., electricity price discounts and construction subsidies).

(IV) Facing the carbon peaking and carbon neutrality goals and sustainable development, there is an urgent need to address the synergy between regional balanced development and energy transition [51]. Establish and improve a coordinated development mechanism for joint motor automobile pollution control. Strengthen communication and cooperation between cities, coordinate solutions to significant regional challenges in energy transition, and promote the rational flow and efficient allocation of resources. Construct a province-wide dynamic monitoring and scientific assessment system for motor automobile emissions, regularly monitor and evaluate regional energy consumption status, and provide a scientific basis for policy formulation.

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D.W.; funding acquisition, D.W. and J.W. All authors have read and agreed to the published version of the manuscript.

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