The Potential of Electric Vehicles as a Low-Emission Transportation Alternative: A Comparative Analysis with Internal Combustion Engine Vehicles and Its Relevance to Indonesia

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Abstract

The transportation sector is one of the major contributors to greenhouse gas emissions that contribute to global climate change. Electric Vehicles (EVs) have been widely developed as a low-emission transportation alternative; however, their effectiveness compared with Internal Combustion Engine (ICE) vehicles still requires further study. This study aims to analyze the comparison of carbon emissions between electric vehicles and Internal Combustion Engine (ICE) vehicles, identify the relationship between vehicle technical characteristics and carbon emissions, and examine the implications of the research findings for the development of electric vehicle adoption in Indonesia. This study uses a quantitative approach by utilizing secondary data from 3,548 vehicles, consisting of 848 electric vehicles and 2,700 Internal Combustion Engine (ICE) vehicles. The analysis was conducted using descriptive statistics, the Independent Sample T-Test, and Pearson correlation. The results show that electric vehicles have an average carbon emission of 105.65 g/mile, which is much lower than that of Internal Combustion Engine (ICE) vehicles, at 335.79 g/mile. The results of the Independent Sample T-Test show that electric vehicles produce significantly lower carbon emissions than Internal Combustion Engine (ICE) vehicles. The correlation analysis shows that energy efficiency (Miles Per Gallon/MPG) is the variable that has the strongest relationship with carbon emissions, whereas vehicle weight and engine power show relatively weak relationships with carbon emissions. The analysis of transportation development in Indonesia shows that electric vehicle sales continued to increase during the period from 2020 to 2024; however, energy consumption in the transportation sector is still dominated by oil fuel with a proportion of more than 99%. These findings show that electric vehicles have greater potential to support carbon emission reduction, although the transition toward a low-emission transportation system is still progressing gradually and requires support through policies, infrastructure, and the development of cleaner energy.

Keywords: *electric vehicles; carbon emissions; energy efficiency; internal combustion engine vehicle; low-emission transportation*

1. Introduction

Climate change has become one of the most important global challenges today. One of the main causes of climate change is the increasing emission of greenhouse gases (GHGs) resulting from various human activities. Among these activities, the transportation sector is one of the significant contributors to emissions. In 2024, the transportation sector generated approximately nine billion metric tons of CO_2 [1]. This figure indicates that emissions generated by the transportation sector remain very high, with the majority originating from vehicles used on roads, such as cars, buses, trucks, and motorcycles. In addition to generating large amounts of emissions, the transportation sector has also shown an increasing trend in emissions over time. Transportation emissions increased at an average annual growth rate of 1.7% during the period from 1990 to 2022 [2]. This condition indicates that the transportation sector remains one of the major challenges in efforts to reduce carbon emissions. This issue has encouraged many countries to develop more environmentally friendly transportation technologies to reduce dependence on fossil fuels and reduce carbon emissions. Among the various transportation technologies currently being developed, Electric Vehicles (EVs) have become one of the fastest-growing solutions. This technology has been widely adopted and has attracted attention from governments, industries, and the public. Electric vehicles use electrical energy as their primary power source, thereby reducing the use of fossil fuels. Furthermore, electric vehicles are also considered capable of producing lower emissions than Internal Combustion

Engine (ICE) vehicles. Therefore, electric vehicles are often promoted as one of the alternatives for low-emission transportation.

The development of electric vehicles is also reflected in the increasing number of sales across various countries. Global electric vehicle sales exceeded 17 million units in 2024, representing an increase of more than 25% compared with the previous year, supported by declining battery production costs, the development of charging infrastructure, and various incentive policies implemented by governments to encourage the adoption of electric vehicles [3]. This growth is expected to continue, making electric vehicles an increasingly larger part of the global vehicle market. Although electric vehicles have experienced rapid development and are often regarded as a more environmentally friendly transportation solution, their effectiveness in reducing carbon emissions continues to be investigated. Various studies have been conducted to measure the extent to which electric vehicles contribute to reducing carbon emissions in the transportation sector. Although electric vehicles offer various advantages, further scientific studies are still required to confirm their effectiveness in reducing carbon emissions. Numerous studies have shown that electric vehicles produce lower emissions during the use phase than Internal Combustion Engine (ICE) vehicles [4]. Therefore, many researchers consider electric vehicles to be one of the alternatives with the potential to help reduce emissions in the transportation sector. However, the environmental benefits of electric vehicles are also influenced by the source of electricity used for charging, meaning that the magnitude of emission reduction may vary across different regions [5]. If electricity is generated from fossil fuel-based power plants, such as coal- or oil-fired power plants, emissions are still produced during the electricity generation process. Since various factors influence the environmental benefits of electric vehicles, studies directly comparing electric vehicles with internal combustion engine vehicles are required. Such comparisons are intended to provide a clearer understanding of the differences in characteristics between the two types of vehicles. Through these comparisons, it can be determined to what extent electric vehicles are capable of reducing emissions compared with ICE vehicles.

In Indonesia, the transportation sector is one of the significant contributors to greenhouse gas (GHG) emissions. In 2022, this sector generated 159 million tons of CO_2 emissions, with approximately 94.69% originating from land transportation. To support emission reduction efforts, the Indonesian government has promoted the development of the electric vehicle ecosystem through various policies aimed at accelerating the adoption of electric vehicles and supporting the transition toward a more sustainable transportation system [6]. Several previous studies have examined various aspects related to electric vehicles. Study [7] showed that electric vehicles have significant environmental benefits, although battery production and recycling processes still pose environmental challenges. Study [8] analyzed the operational cost comparison of electric, gasoline, and diesel vehicles in Indonesia, whereas Study [9] examined the development of electric vehicles from market and infrastructure perspectives in the context of Indonesia and South Korea. Although these studies have made important contributions, most of them have focused separately on environmental, economic, or policy aspects. Studies directly comparing the carbon emission characteristics of electric vehicles and Internal Combustion Engine (ICE) vehicles using large-scale vehicle datasets, while also analyzing the relationship between vehicle technical characteristics and carbon emissions, remain relatively limited [10]. Therefore, this study was conducted to compare carbon emissions between electric vehicles and Internal Combustion Engine (ICE) vehicles, identify the relationship between vehicle technical characteristics and carbon emissions, and examine the implications of the findings for the development of electric vehicle adoption and the transition toward low-emission transportation in Indonesia.

2. Materials and Methods

Based on the research problems and objectives described in the Introduction section, the research stages were developed as a guideline for conducting the study. These stages are presented in the form of a flowchart in Figure 1.

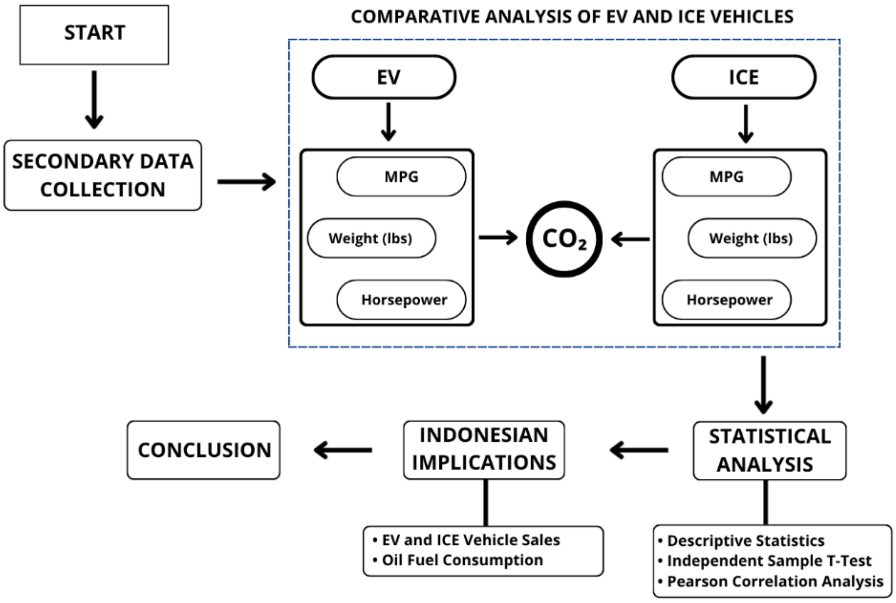

Figure 1. Flowchart of the research stages.

This study uses a quantitative approach by utilizing secondary data to compare the characteristics of carbon emissions and energy efficiency between Electric Vehicles (EVs) and Internal Combustion Engine (ICE) vehicles. The data used consist of 3,548 vehicle records containing information on vehicle type, vehicle year, carbon emissions (CO_2), energy efficiency (MPG), vehicle weight, and engine power (horsepower). In addition to the vehicle dataset, this study also uses supporting data on EV and ICE sales in Indonesia obtained from the Indonesian Automotive Industry Association [11], as well as transportation sector Oil Fuel consumption data obtained from [12]. These data are used to support the analysis of the implications of the research findings for the development of the transition toward low-emission transportation in Indonesia. The research variables used are presented in Table 1.

Table 1. Research variables.

No	Variable	Column Name	Unit
1	Vehicle type	Type	–
2	Vehicle year	Year	Year
3	Carbon emissions	CO_2 Emission	g/mile
4	Energy efficiency	MPG Combined	MPG
5	Vehicle weight	Weight	lbs
6	Engine power	Horsepower	HP

Before the analysis was conducted, the data were examined to ensure the completeness and consistency of each variable. Incomplete or inconsistent data were excluded from the analysis. Subsequently, the data that met the established criteria were organized into a structured dataset for further analysis [13]. The analysis began with a comparative analysis between EV and ICE vehicles based on the variables of CO_2 emissions, MPG, weight, and horsepower. Subsequently, statistical analyses were performed, including descriptive analysis, the Independent Samples *t*-Test, and Pearson correlation analysis. Descriptive analysis was used to describe the characteristics of the data based on the minimum, maximum, mean, and standard deviation values [14]. The Independent Samples *t*-Test was used to examine the significance of differences in carbon emissions between EV and ICE vehicles. Meanwhile, Pearson correlation was used to identify the relationships of MPG, weight, and horsepower with carbon emissions. The Pearson correlation coefficient was calculated using Equation 1.

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})\,(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}} \tag{1}$$

The value of the Pearson correlation coefficient ranges from −1 to +1. A positive value indicates a positive relationship between two variables, whereas a negative value indicates an inverse relationship. The closer the coefficient is to ±1, the stronger the relationship between the analyzed variables. To examine the implications of the research findings for the Indonesian context, an analysis was conducted on the development of EV and ICE vehicle sales as well as oil fuel consumption in the transportation sector. The final stage was drawing conclusions based on the overall results of the analyses conducted.

3. Results and Discussion

Before the comparative analysis was conducted, the data distribution by vehicle type was analyzed to provide an overview of the composition of the data used in this study. The analyzed dataset consisted of 3,548 vehicles, including 848 Electric Vehicles (EVs) and 2,700 Internal Combustion Engine (ICE) vehicles. The distribution of vehicles by vehicle type is shown in Figure 2.

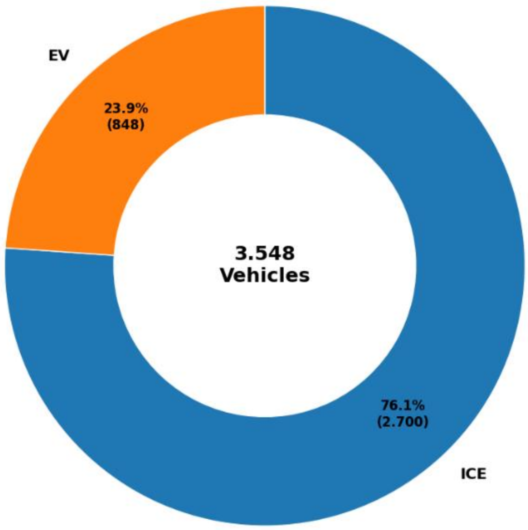

Figure 2. Distribution of vehicles by vehicle type.

Internal Combustion Engine (ICE) vehicles dominated the dataset used in this study, accounting for 76.1% of the total data, whereas Electric Vehicles (EVs) accounted for 23.9%. This difference in proportion indicates that Internal Combustion Engine (ICE) vehicles were more numerous than Electric Vehicles (EVs) in the analyzed dataset.

3.1 [Descriptive Statistics of the Research Variables]

Descriptive analysis was conducted to provide an overview of the characteristics of EV and ICE vehicles used in this study. The descriptive statistics include the minimum, maximum, mean, and standard deviation values for each research variable. The results of the descriptive analysis are presented in Table 2.

Table 2. Descriptive statistics of the research variables.

Variable	Vehicle Type	Minimum	Maximum	Mean	Standard Deviation
CO_2 (g/mile)	EV	55.80	166.80	105.65	19.19
CO_2 (g/mile)	ICE	189.00	754.10	335.79	83.95
MPG	EV	70.00	143.90	108.28	12.64
MPG	ICE	12.00	48.00	27.89	6.04
Weight (lbs)	EV	2,800	6,368	4,226.73	701.87

Variable	Vehicle Type	Minimum	Maximum	Mean	Standard Deviation
Weight (lbs)	ICE	2,000	5,717	3,602.37	598.29
Horsepower (HP)	EV	150	554	283,08	78,58
Horsepower (HP)	ICE	100	397	209,75	58,63

The analysis results show a clear difference between Electric Vehicles (EVs) and Internal Combustion Engine (ICE) vehicles. Electric vehicles produce an average carbon emission of 105.65 g/mile, whereas ICE vehicles reach 335.79 g/mile. In addition to producing lower carbon emissions, electric vehicles also have higher energy efficiency, with an average MPG value of 108.28, whereas ICE vehicles have an average MPG value of only 27.89. Although electric vehicles have higher average vehicle weight and engine power, these characteristics are not accompanied by an increase in carbon emissions. These findings indicate that electric vehicles are capable of providing better energy efficiency while producing lower carbon emissions than Internal Combustion Engine (ICE) vehicles [15]. This difference was subsequently confirmed through statistical testing, which showed that the carbon emissions of electric vehicles and Internal Combustion Engine (ICE) vehicles differ significantly. Therefore, the lower carbon emissions of electric vehicles are not the result of random variation but instead reflect differences in emission characteristics between the two types of vehicles. These results strengthen the findings of previous studies, which reported that electric vehicles have greater potential for reducing carbon emissions than conventional vehicles, particularly during the vehicle use phase [16]. To provide a clearer overview of the carbon emission distribution characteristics of both vehicle groups, a boxplot analysis was performed, as presented in Figure 3.

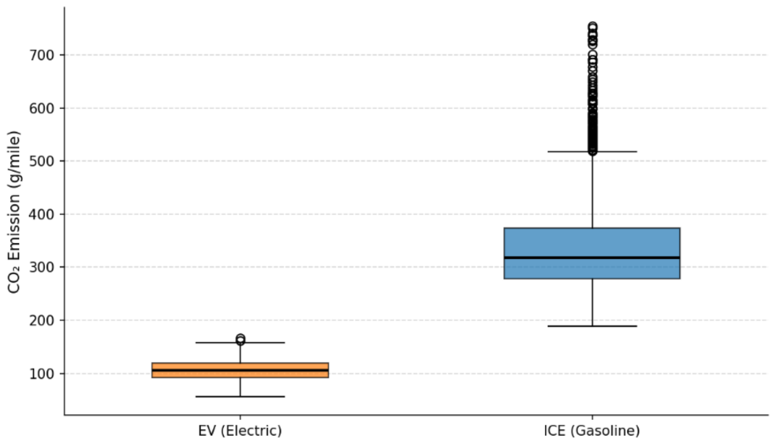

Figure 3. Comparison of the carbon emission distribution between Electric Vehicles (EVs) and Internal Combustion Engine (ICE) vehicles.

The results show that the emission distribution of electric vehicles falls within a lower range than that of ICE vehicles. The median carbon emission of electric vehicles is approximately 100 g/mile, whereas the median carbon emission of ICE vehicles is above 300 g/mile. In addition, the distribution of ICE vehicle data appears to be wider than that of electric vehicles, indicating greater variation in emissions among vehicles. Several outlier values with emission levels substantially higher than those of the majority of other vehicles were also identified in the ICE group. Overall, these results indicate that electric vehicles have lower and more consistent carbon emission characteristics than Internal Combustion Engine (ICE) vehicles. These findings are consistent with previous studies reporting that electric vehicles produce lower operational emissions and exhibit better environmental performance than conventional fossil fuel-powered vehicles [17]. The visualization results of the relationships among the variables are presented in Figure 4.

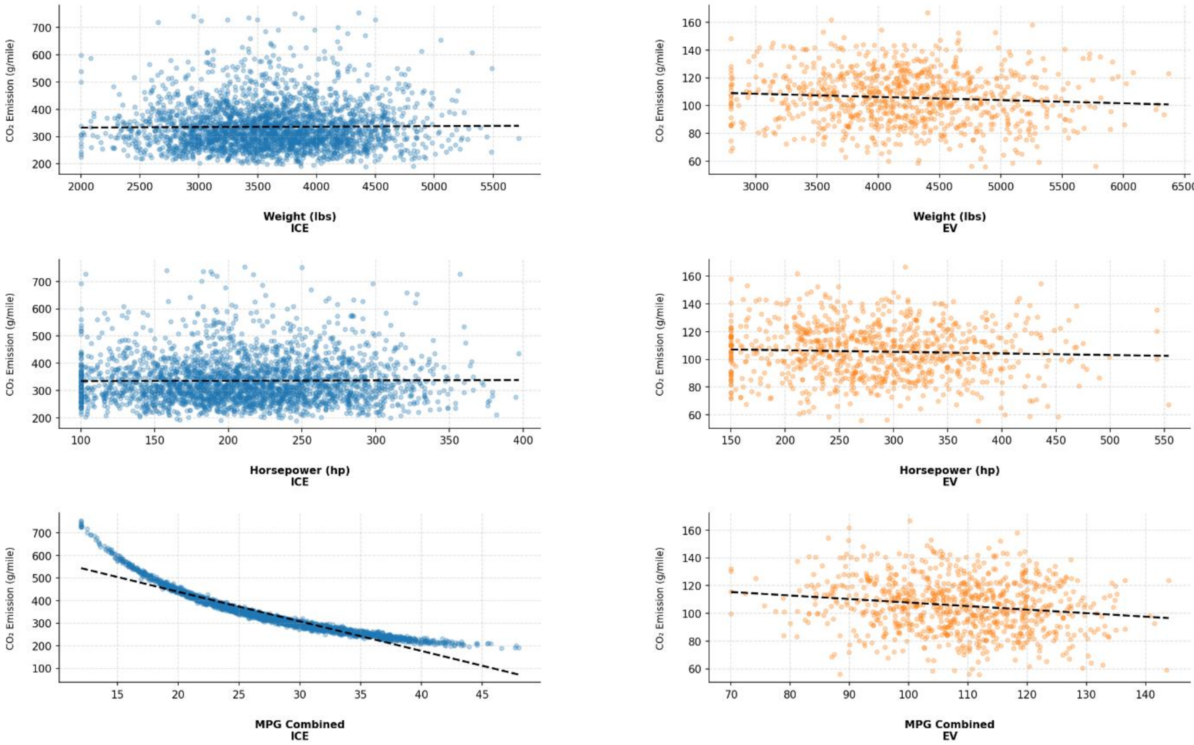

Figure 4. Relationship of vehicle weight, engine power, and energy efficiency with carbon emissions in EV and ICE vehicles.

The figure shows that the relationship between vehicle weight and carbon emissions in both ICE and EV vehicles tends to be weak. The relatively random distribution of the data, together with the nearly flat trend line, indicates that an increase in vehicle weight is not directly followed by a significant change in carbon emissions. Similar findings are also observed in the relationship between engine power and carbon emissions, where the data distribution pattern indicates a very weak relationship in both vehicle groups. In contrast to these two variables, energy efficiency shows a clearer relationship with carbon emissions. In ICE vehicles, an increase in Miles per Gallon (MPG) is followed by a considerable decrease in carbon emissions. This pattern is reflected by a downward trend line and a data distribution that follows a negative relationship. These findings are consistent with previous studies reporting that improvements in fuel efficiency are consistently followed by reductions in CO_2 emissions, particularly in Internal Combustion Engine (ICE) vehicles [18]. Meanwhile, in EV vehicles, the relationship between MPG and carbon emissions also shows a negative trend, although the strength of the relationship is weaker than that observed in ICE vehicles. This difference may be influenced by the characteristics of the electric vehicle powertrain system and the energy source used during the charging process. The results of this study indicate that energy efficiency is the variable with the strongest relationship with carbon emissions compared with vehicle weight and engine power. In other words, improving energy efficiency has the potential to provide a greater impact on reducing carbon emissions than changes in vehicle weight or engine power. These findings also support previous studies concluding that improving vehicle energy efficiency is one of the most effective strategies for reducing carbon emissions in the transportation sector [19]. To identify the relationship between vehicle technical variables and carbon emissions, Pearson correlation analysis was performed. The results of the analysis are presented in Table 3.

Table 3. Pearson correlation analysis results.

Variable	EV	Interpretation	ICE	Interpretation
MPG vs. CO_2	-0.168	Very weak	-0.942	Very strong
Vehicle weight vs. CO_2	-0.084	Very weak	0.012	Very weak
Engine power vs. CO_2	-0.047	Very weak	0.009	Very weak

The analysis results indicate that MPG energy efficiency has a negative relationship with carbon emissions in both vehicle groups. This relationship is strongest in ICE vehicles, indicating that improvements in energy efficiency are accompanied by greater reductions in carbon emissions. In contrast, the relationship between MPG energy efficiency and carbon emissions in EV vehicles is also negative, although its strength is considerably weaker. Meanwhile, vehicle weight and engine power show only very weak relationships with carbon emissions in both EV and ICE vehicles. These findings indicate that energy efficiency is the technical characteristic most strongly associated with carbon emissions compared with vehicle weight and engine power in both types of vehicles.

3.2 Implications of the Findings for the Transportation Transition in Indonesia

To provide an overview of the relevance of the research findings to the national transportation context, a descriptive analysis was conducted on the development of electric vehicle sales and Internal Combustion Engine (ICE) vehicle sales in Indonesia. In addition, transportation sector energy consumption data were used to describe the energy use conditions in the sector. The results of the analysis are presented in Figure 5.

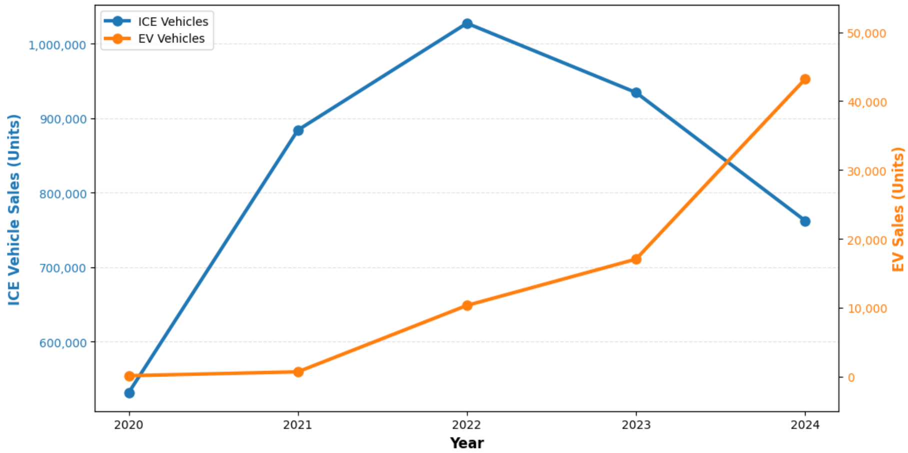

Figure 5. Development of Internal Combustion Engine (ICE) vehicle sales and Electric Vehicle (EV) sales in Indonesia.

Electric vehicle sales show a significant upward trend, particularly from 2022 to 2024. The number of electric vehicle sales increased from 125 units in 2020 to 43,188 units in 2024 [20]. This increase indicates the growing adoption of electric vehicles in Indonesia, supported by technological developments, government policies, and increasing attention to environmental issues and energy efficiency [21]. On the other hand, Internal Combustion Engine (ICE) vehicle sales increased until reaching their peak in 2022, before showing a declining trend in 2023 and 2024. Nevertheless, ICE vehicle sales remain substantially higher than electric vehicle sales and therefore continue to dominate the national vehicle market. This condition indicates that the transition from fossil fuel-powered vehicles to electric vehicles has begun, although it is still progressing gradually. These results are consistent with the main findings of this study, which indicate that electric vehicles have lower carbon emissions than ICE vehicles. The increase in the number of electric vehicles has not yet been followed by significant changes in the energy consumption pattern of the transportation sector. Several studies have shown that the success of the transition toward low-emission transportation is influenced not only by the growth in the number of electric vehicles but also by changes in the energy structure and the level of dependence on fossil fuels. Therefore, to provide an overview of energy use in Indonesia's transportation sector, an analysis of the percentage of Oil Fuel consumption was conducted, as presented in Table 4.

Table 4. Percentage of Oil Fuel consumption in Indonesia's transportation sector.

Year	Oil Fuel (%)
2020	99,87
2021	99,88
2022	99,88

Energy consumption in Indonesia's transportation sector is still dominated by oil fuel, accounting for a proportion ranging from 99.86% to 99.89% during the observation period. The stability of this proportion indicates that national transportation activities still depend heavily on fossil fuel-based energy. This condition indicates that changes in the energy structure of the transportation sector are still progressing slowly. When related to the development of vehicle sales, the increase in electric vehicle adoption during the period from 2020 to 2024 has not yet been followed by significant changes in the national transportation energy consumption pattern. Although electric vehicle sales continue to increase, Internal Combustion Engine (ICE) vehicles still dominate the vehicle population, causing oil fuel to remain the primary energy source. As a result, the impact of increasing electric vehicle adoption on changes in the national energy structure remains relatively limited. These findings show that the transition toward low-emission transportation requires a long period due to the high dominance of fossil fuel-powered vehicles in the transportation system [22]. These results also support the main findings of this study, which show that electric vehicles have lower carbon emission levels than Internal Combustion Engine (ICE) vehicles. However, the success of the transition toward a low-emission transportation system is determined not only by the growth in the number of electric vehicles but also by changes in the overall energy consumption structure [23]. Therefore, increasing the adoption of electric vehicles needs to be supported by the development of infrastructure, the provision of cleaner energy, and sustainable policies in order to provide a more significant impact on energy consumption and emission reduction in the transportation sector in the future.

4. Conclusion

This study analyzes the comparison of carbon emissions between Electric Vehicles (EVs) and Internal Combustion Engine (ICE) vehicles based on data from 3,548 vehicles covering the period from 2010 to 2024. There are three main findings generated from this study. First, electric vehicles produce an average carbon emission of 105.65 g/mile, which is 68.5% lower than that of ICE vehicles, which reaches 335.79 g/mile. The statistical test results confirm that the difference in carbon emissions between the two types of vehicles is significant, indicating that electric vehicles have lower emission characteristics than Internal Combustion Engine (ICE) vehicles. In addition, electric vehicles also show smaller variations in carbon emissions than ICE vehicles, indicating more consistent emission characteristics. Second, the Pearson correlation analysis shows that energy efficiency (MPG) is the technical variable that has the strongest relationship with carbon emissions, particularly in ICE vehicles. In contrast, vehicle weight and engine power show very weak relationships with carbon emissions in both types of vehicles. These findings indicate that improving energy efficiency plays a greater role in reducing carbon emissions than changes in vehicle weight or engine power. Third, the analysis of transportation conditions in Indonesia shows that electric vehicle sales increased from 125 units in 2020 to 43,188 units in 2024. Nevertheless, Internal Combustion Engine (ICE) vehicles still dominate the national vehicle market, and energy consumption in the transportation sector still depends heavily on oil fuel, accounting for approximately 99.86% to 99.89% during the period from 2020 to 2024. This condition indicates that although electric vehicle adoption continues to grow, the transition toward a low-emission transportation system in Indonesia is still progressing gradually. Based on these findings, accelerating the adoption of electric vehicles, supported by the development of charging infrastructure, the provision of cleaner energy, and sustainable policies, has the potential to provide a more significant impact on reducing carbon emissions in Indonesia's transportation sector in the future.

Authors' Contributions

Yud.P.K. conceived the study, conducted the experiments, analyzed the data, and drafted the manuscript. D.L. supervised the research, contributed to the methodology, and reviewed the manuscript. Yu.P.K., V.I.F.M., and N.Q. contributed to data analysis, validation, and manuscript revision. D.L. supervised the overall project and critically reviewed the manuscript. All authors read and approved the final manuscript.

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