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Toward Low-Carbon Mobility: Greenhouse Gas Emissions and Reduction Opportunities in Thailand's Road Transport Sector

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Abstract

Road transportation is a major contributor to greenhouse gas (GHG) emissions in Thailand. This study assesses the potential for GHG mitigation in the road transport sector from 2018 to 2030. Emission factors for various vehicle types and technologies were derived using the International Vehicle Emissions (IVE) model. Emissions were then estimated based on country-specific vehicle data. In the baseline year 2018, total emissions were estimated at 23,914.02 $GgCO_2eq$, primarily from pickups (24.38%), trucks (20.96%), passenger cars (19.48%), and buses (16.95%). Multiple mitigation scenarios were evaluated, including the adoption of electric vehicles (EVs), improvements in fuel efficiency, and a shift to renewable energy. Results indicate that transitioning all newly registered passenger cars (PCs) to EVs while phasing out older models could lead to a 16.42% reduction in total GHG emissions by 2030. The most effective integrated scenario, combining the expansion of electric vehicles with improvements in internal combustion engine efficiency, could achieve a 41.96% reduction, equivalent to 18,378.04 $GgCO_2eq$. These findings highlight the importance of clean technology deployment and fuel transition policies in meeting Thailand's climate goals, while providing a valuable database to support strategic planning and implementation.

Keywords: road transport; greenhouse gas emission; transport decarbonization; electric vehicles; sustainable mobility

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1. Introduction

Climate change represents a critical for sustainable development as a significant threat to the global community. The buildup in the atmosphere of greenhouse gases (GHGs) is the primary cause of climate variation [1,2]. As a Southeast Asian country, Thailand is a country that is especially vulnerable to the consequences of climate change. The nation is experiencing higher average temperatures, and more frequent and severe floods, droughts, and storms. The adverse effects pose significant risks to key economic sectors, such as agriculture, tourism, and industry [3,4].

Greenhouse gas emissions in Thailand are driven by economic developments, the growth of the population, and urbanization. In 2020, final energy consumption was 77,340 kilotonnes of oil equivalent (ktoe), reflecting a 9.76% decline from 2019 due to the economic disruptions caused by the Coronavirus disease 2019 (COVID-19) pandemic. Most (86.40%) of this energy was used for commercial activities. Petroleum products constituted the predominant share of energy sources (48.00%), followed by electricity (21.67%), coal

and its products (10.32%), renewable energy (8.69%), natural gas (6.40%), and traditional renewable energy (4.92%). Among economic sectors, transport was the largest energy consumer (38.40%), followed closely by industry (37.29%). The residential sector accounted for 13.12%, while the commercial and agricultural sectors consumed 8.19% and 3.00%, respectively [5]. The patterns underscore the reliance on fossil fuels and the significant influence of transportation and industry on Thailand's emissions profile.

Thailand's National Greenhouse Gas Inventory, as presented in the Fourth Biennial Update Report (BUR), was prepared in accordance with the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. The country systematically monitors greenhouse gas emissions from all sources and removals for the purpose of reporting to the UNFCCC. The Kyoto Protocol specifies six main types of reported greenhouse gas emissions: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) [4]. In 2019, Thailand's total direct emissions increased from 245,899.56 $GgCO_2eq$ in 2000 to 372,716.86 $GgCO_2eq$, reflecting an average annual increase of 2.21%. In 2019, net greenhouse gas emissions amounted to 280,728.34 $GgCO_2eq$, inclusive of land use, land use change, and forestry (LULUCF), reflecting an average annual increase of 1.79% [5].

Between 2000 and 2019, the energy sector emerged as the biggest contributor of GHG emissions in Thailand, experiencing a significant rise of 57.96%, rising from 165,092.40 $GgCO_2eq$ in 2000 to 260,772.69 $GgCO_2eq$ in 2019. The primary contributor to greenhouse gas emissions within the energy sector is the combustion of fuels, particularly in grid-connected electricity and heat production, accounting for 39.63% of total emissions. Additional significant contributors comprise the transportation sector, manufacturing industries, construction, and several smaller sub-sectors. In 2019, the amount of greenhouse gas emissions from the transport sector was 76,923.01 $GgCO_2eq$, constituting 29.50% of total greenhouse gas emissions of the energy sector. Greenhouse gas emissions from transportation in Thailand were most profoundly affected by road transport, which contributed 95.60% of the total [5].

The transportation sector being one of the major contributors to GHG emissions, thereby exacerbating global warming through the combustion of petroleum-based fuels. In internal combustion engines (ICEs), hydrocarbons in gasoline and diesel react with oxygen (O_2) during combustion to produce energy. Under the ideal conditions, this process leads to complete combustion, resulting in the formation of carbon dioxide (CO_2) and water vapor (H_2O). However, in practice, the incomplete combustion and high-temperature reaction often results in the generation of further greenhouse gases (such as CH_4 and N_2O) and air pollutants such as carbon monoxide (CO), nitrogen oxides (NO_x), hydrocarbons (HC), and particulate matter (PM). Emissions depend on the type of fuel type, the engine efficiency, the engine technology, the combustion process, and on the installation of pollution control devices [6,7]. The growth of the economy and the population also has meant a growth in the need to move around the country, with people and goods. Burning fossil fuel, for example, petrol and diesel produce carbon dioxide (CO_2) and various greenhouse gases, such as methane (CH_4), nitrous oxide (N_2O), and hydrofluorocarbons (HFCs), into the atmosphere [7,8]. Passenger cars, medium- and heavy-duty trucks, and light trucks represent the primary sources of greenhouse gas emissions associated with transportation. These sources represent more than 50% of emissions from the transportation sector [7,9].

The number of vehicles registered in Thailand rose from 20.8 million in 2000 to 44.3 million in 2023, representing an average annual growth rate of 3.54%. The Motor Vehicle Act recorded 42.9 million registrations in 2023, while the Land Transport Act recorded 1.3 million. In 2023, motorcycles constituted 50.87% of registered vehicles in Thailand, followed by passenger cars at 26.68%, vans and pickups at 16.02%, and trucks at

2.81%. More than 95% of transportation fuel is derived from petroleum, predominantly in the form of gasoline and diesel [10]. The rising trend in energy consumption within the transportation sector may result in elevated emissions of greenhouse gases and air pollutants [11].

Thailand submitted the Long-Term Low Greenhouse Gas Emission Development Strategy (LT-LEDS) to the United Nations Framework Convention on Climate Change (UNFCCC) to address the climate crisis. This strategy outlines Thailand's targets to achieve carbon neutrality by 2050 and net-zero greenhouse gas emissions by 2065, focusing on actions to mitigate the most severe impacts of climate change. The Nationally Determined Contribution (NDC) Action Plan is essential for outlining the measures necessary to achieve its mitigation target by 2030. The revised NDC target for transportation seeks a 30–40% reduction relative to Business as Usual (BAU), an increase from the original target of 20–25% from BAU levels by 2030. The sectoral action plans for energy, transportation and other relevant sectors were formulated to delineate specific measures and the agencies responsible for their implementation [12].

The transport sector presents the greatest opportunity for reducing greenhouse gas emissions [13]. The NDC Sectoral Action Plan for the Transport Sector, covering the years 2021–2030, was created by the Office of Transport and Traffic Policy and Planning (OTP), with the objective of reducing greenhouse gas emissions by millions of tons of carbon dioxide equivalent [5]. Thailand's Nationally Determined Contribution (NDC) Roadmap (2021–2030) outlines mitigation strategies for the transport sector, which encompass reducing travel demand, facilitating a modal shift or promoting low-emission transport modes, and improving energy efficiency [4]. Minimizing greenhouse gas emissions in the land transport sector is crucial for achieving the targets established in Thailand's LT-LEDS. Thailand's Nationally Appropriate Mitigation Actions (NAMAs) and Climate Change Master Plan target a 7–20% reduction in emissions from the energy and transport sectors compared to the business-as-usual (BAU) scenario. Measures include mitigation actions within the energy and transport sectors, supported by government policies that promote electric vehicles (EVs), improve vehicle efficiency, develop transportation systems, and encourage alternative energy sources [14–16].

Thailand's greenhouse gas emission inventory has been developed following the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, based on the availability of data and the required level of detail. Accurate activity data and emission factors (EF) are crucial to the emission inventory's reliability since they significantly affect inventory uncertainty. The top-down reference approach integrates activity data utilizing national energy supply statistics and the standard IPCC emission factors categorized by fuel type. The bottom-up approach uses detailed activity data, incorporating various parameters and higher levels of disaggregation (e.g., operational conditions, vehicle technology, and distance traveled by vehicles), together with emission factors (kg/km) [17]. Transport models provide specific input parameters, including average vehicle speed and its temporal variation, which improve the accuracy and representation of calculated vehicular emissions [18].

Estimating emissions from road transport is a multifaceted procedure that necessitates the integration of greenhouse gas emission rates with vehicle activity data and emission factors [19,20]. Transport emission factors describe pollutant emissions from vehicles based on their activities. These parameters are obtained from experimental data or model simulations and can be employed for calculating vehicle emissions. Dependence exclusively on constant greenhouse gas emission factors from the IPCC database may prove insufficient for precise emission assessments or the development of effective mitigation strategies within the transportation sector. The existing database for GHG emissions should be updated to take into account improvements in GHG inventory quality and to indicate

potential seasoned mitigation measures derived from the plans used. This database offers an adequate basis for evaluating the effectiveness and efficiency of measures. A literature review showed that there are important gaps in the study of greenhouse gas emissions from the road transportation sector, particularly as far as detailed parameters such as engine technology, fuel type characteristics, and VKT are concerned. Calculating road transportation GHG emissions depends on specific information about fuel types, engine standards, vehicle technologies, as well as real-world emission factors and country-specific conditions to better understand reasonable factors influencing emissions change [21,22].

The objectives of this study are to assess greenhouse gas emissions and mitigation options for emissions reduction in Thailand's transport sector. The IVE model was employed to derive updated greenhouse gas emission factors utilizing national measurement data. Future trends in greenhouse gas emissions and reductions were assessed in accordance with national strategies and relevant policies and compared to a baseline business-as-usual (BAU) scenario. The results could serve as a validation tool for the GHG emission inventory by supporting the validation of the reliability of activity data and emission factors. This information will be useful in formulating effective strategies for GHG emission reduction and enhancing collaborative initiatives for addressing climate change under the UNFCCC.

2. Materials and Methods

2.1. Scope of Study

Figure 1 depicts the key components and data flows used in estimating GHG emissions from road transport, such as vehicle kilometers traveled (VKT), emission factors, fuel types, and operating conditions. It highlights the use of traffic data, emission models (IVE), and policy scenarios to support emission inventories and mitigation measures. The process comprises four sequential steps:

1. Collecting relevant country-specific data on vehicle activity from primary and secondary sources, covering the total number and percentages of vehicles registered in Thailand, fuel type, engine technology, vehicle kilometers traveled (VKT), driving cycles, number of start-ups, and the measurement data of greenhouse gas emissions from the Automotive Emission Laboratory (AEL).
2. Developing emission factors utilizing the International Vehicle Emissions (IVE) model (version 2.0) informed by the emission database from the Automotive Emission Laboratory (AEL).
3. Estimating greenhouse gas emissions from vehicles for the base year 2018, in accordance with the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.
4. Assessing vehicle growth rates across all types and assessing future trends in greenhouse gas emissions, considering both the baseline situations and reduction scenarios. Further abatement options were then considered in order to recommend further reduction in the emission of GHGs from the road transportation sector.

The year 2018 was selected as the base year for this study, as it represents a timeframe prior to the outbreak of the coronavirus (COVID-19) pandemic in 2019–2020. The implementation of work-from-home measures during the pandemic resulted in a significant reduction in the number of vehicles on the road. In 2020, emissions experienced a significant reduction, primarily attributed to the effects of the COVID-19 pandemic on travel and various economic activities. In 2021, the increase in overall greenhouse gas emissions was mostly attributed to an increase in CO_2 emissions from fossil fuel burning, coinciding with the recovery of economic activity after the COVID pandemic peak.

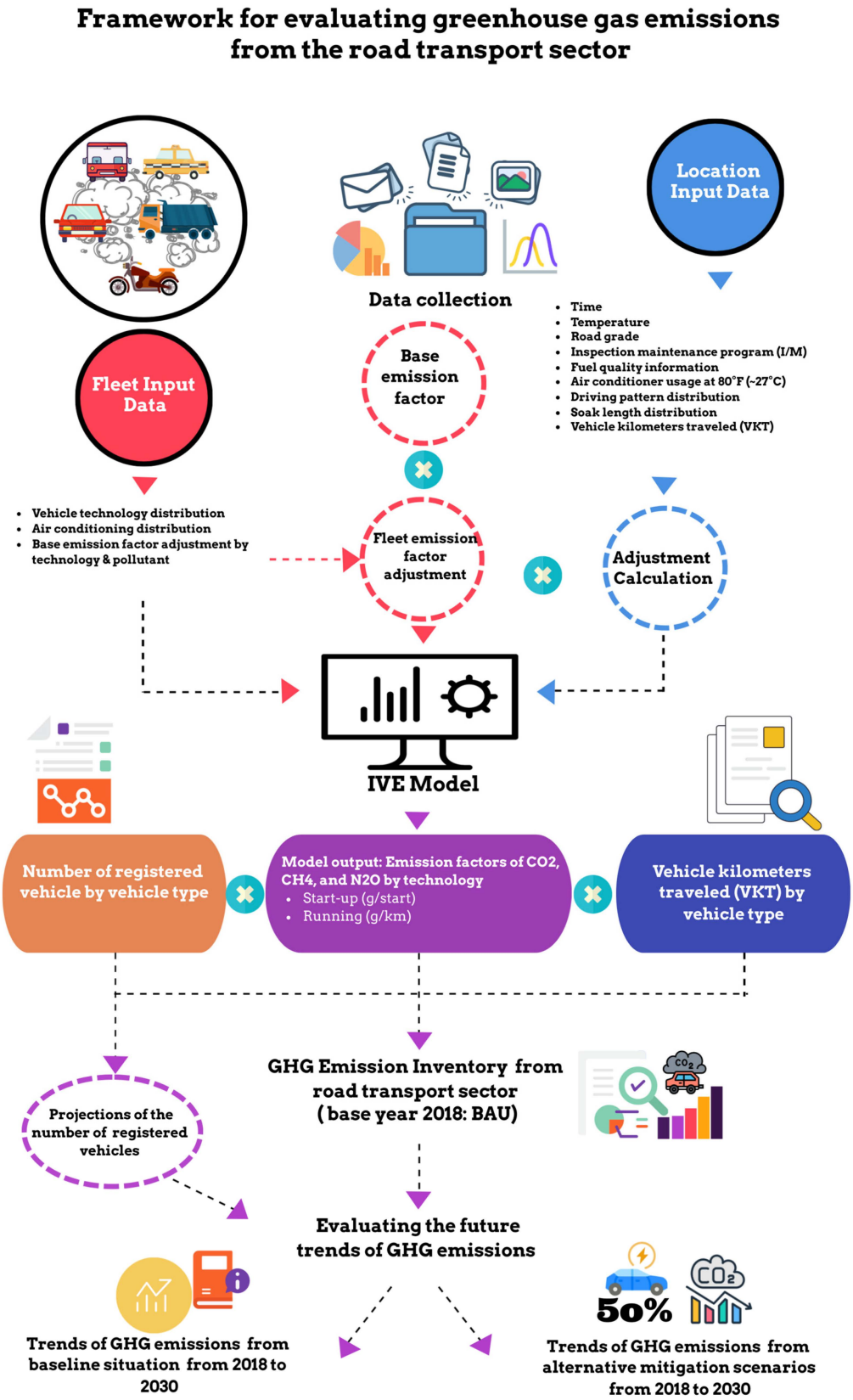


Figure 1. Conceptual framework for evaluating greenhouse gas emissions from the road transportation sector. Remark: adapted from [23].

2.2. Data Collection

2.2.1. Vehicle Data

Vehicle Type

The registered vehicle data from 1994 to 2020 was acquired from the Department of Land Transportation [10]. In 2018, the base year, registered vehicles represented 99.19% of the total on-road vehicles. Between 1994 and 2020, the annual growth rate of registered vehicles was 4.92%. Vehicle types are classified into eight categories as defined by the Motor Vehicle Act and the Land Transport Acts of Thailand: motorcycles (MCs), passenger cars (PCs), pickups, vans, public motorcycles (PMCs), taxis, buses, and trucks.

The assessment of GHG emissions exclusively regards fuels utilized in domestic road transportation. Six categories of fuel are utilized in the transportation sector: gasoline, gasohol, diesel, biodiesel, liquefied petroleum gas (LPG), and natural gas for vehicles (NGV). The quantity of each fuel utilized in road transportation was obtained from the Department of Land Transportation [10]. The calculation of greenhouse gas emissions from these fuels' combustion includes carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O).

In 2018, Thailand had approximately 39.5 million registered vehicles. Figure 2 shows the contribution of each type of vehicle in the distribution of the total registered vehicles in Thailand, 2018. The observations demonstrate the dominance of motorcycles (52.81%) and light-duty vehicles, including passenger cars and pickups, which account for 23.67% and 16.72%, respectively. These vehicle categories significantly impact traffic flow and emission in the country. The Pollution Control Department (PCD) administers emission rules for on-road vehicles in Thailand, as adopted by the Ministry of Industry (MOI). Presently, automobiles in Thailand adhere to Euro 4 emissions regulations. The Euro 5 emission standard will be adopted for newly manufactured vehicles as an important part of the government's strategy to address particle pollution [24]. Understanding vehicle fleet composition is crucial for precise emissions estimation and designing of specific mitigation strategies.

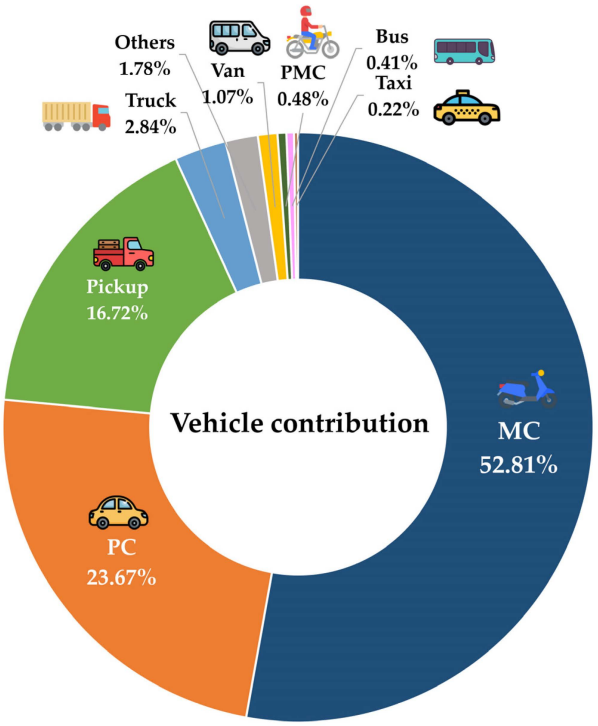


Figure 2. Contribution of registered road vehicles by vehicle type in Thailand, 2018.

Fuel Type

Figure 3 illustrates the distribution of various fuel types, including gasoline, diesel, LPG, NGV, and electric, among major vehicle categories in Thailand for the year 2018. In Thailand, over 95% of fuel utilized for road transportation is derived from petroleum, predominantly in the form of gasoline and diesel. Gasoline-powered vehicles constituted 68.18% of the total, whereas diesel-powered vehicles represented 27.35%. Motorcycles, public motorcycles, and passenger cars predominantly utilized gasoline, accounting for 99.98%, 100%, and 60.48% of these vehicle categories, respectively. In contrast, pickups, vans, trucks, and buses primarily used diesel, accounting for 93.94%, 84.57%, 76.49%, and 75.14% of their respective categories (Figure 3). Furthermore, approximately 27.74% of passenger vehicles utilized diesel fuel. Most taxis utilized CNG gasoline (70.81%), while LPG diesel accounted for 26.23% [10]. The share of fuel combustion modes within each vehicle category is reported in the database, providing important input for the development of approaches to evaluate sectoral GHG emissions and to develop vehicle technology choices, including fuel-switching or electrification strategies.

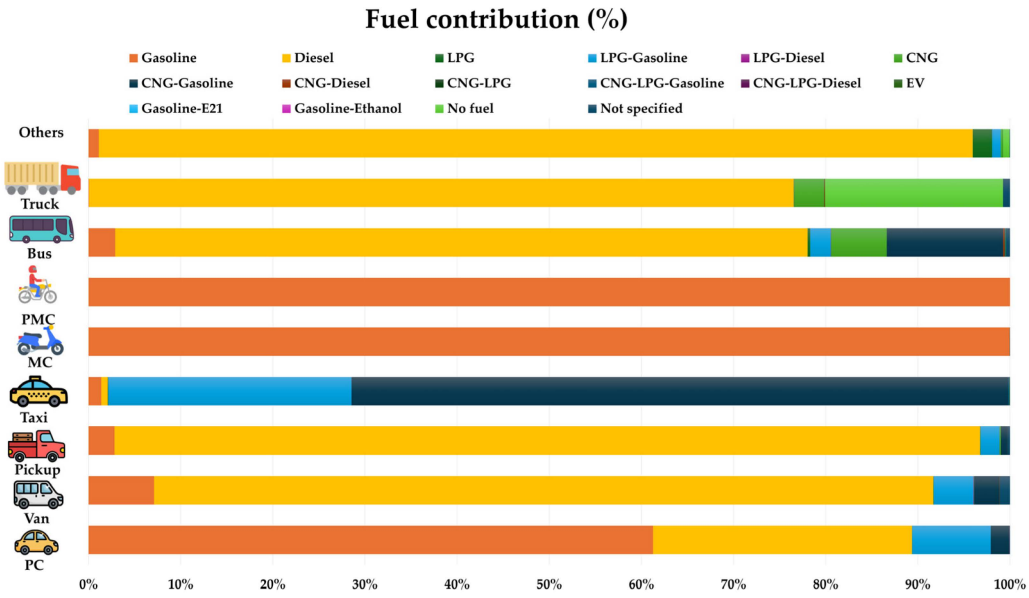


Figure 3. Fuel Type Contribution by Vehicle Type in Thailand, 2018.

Vehicle Age

Figure 4 shows the age distribution of the registered vehicles in Thailand for 2018. The age structure of the vehicle fleet was derived from the Department of Land Transport (DLT), which represents around 34.6 million registered vehicles or 89% of the whole national fleet by 2018 [10]. This large dataset supports the representativeness of the analysis, particularly for commonly used vehicle categories. We also elaborated the categorization by age categories (with 3 years, 3–7 years, 8–15 years, 16–20 years, and beyond 20 years) and the reasons for the inclusion or exclusion of particular vehicle types. The predominant age for passenger cars, motorcycles, public motorcycles, and taxis falls within the 3 to 7-year range. Pickups typically range from 8 to 15 years in age, while vans, trucks, and buses are predominantly over 20 years old (Figure 4). This study focused on motor vehicles not exceeding 20 years in age, excluding taxis, which are subject to a legal lifespan limit of 12 years. Furthermore, the analysis covered buses of all ages, as older models remain operational in Thailand [25]. Older vehicles are typically found to have relatively higher emission factors, attributable to outdated technology and operating conditions for the

engines. Age distribution of vehicles is important when assessing fleet emission efficiency and designing industry-specific abatement measures.

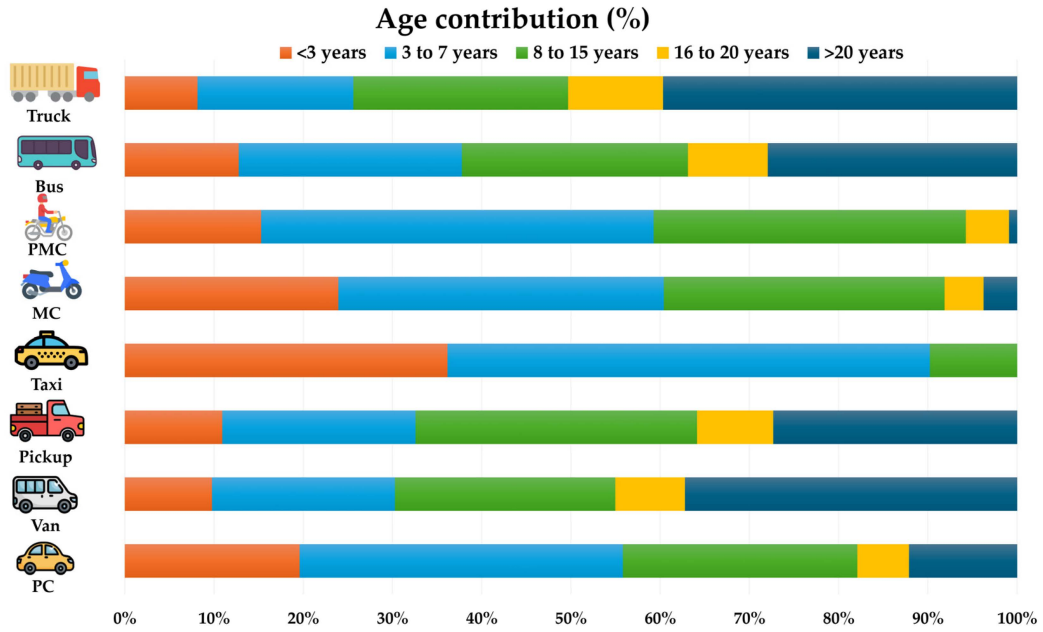


Figure 4. Vehicle age contribution by vehicle type in Thailand, 2018.

Average Vehicle Kilometers Traveled (VKT)

The vehicle kilometers traveled (VKT) for different types of vehicles in Thailand were compiled from multiple sources, including the Pollution Control Department (PCD) emission database, relevant literature [26–28], and supplementary field surveys conducted with private and commercial vehicle owners. These surveys were designed to enhance data accuracy and contextual relevance. Figure 5 presents the estimated average and total annual vehicle kilometers traveled (VKT) by vehicle type in Thailand for the year 2018. Passenger cars (PC) were the highest in terms of total vehicle kilometers traveled (VKT) with 197,288 million km, followed by pickups and motorcycles. Taxi exhibited the highest average vehicle kilometers traveled (VKT) at 114,647 km per year, despite constituting a smaller fleet size. The data indicate individual vehicle usage intensity and national transport activity levels by mode. The previous study also indicates that the survey findings regarding vehicle use, and travel distance correspond with the fuel types used, in comparison to data from the Department of Land Transport. The survey findings indicate the current travel behavior of the population, with most respondents regularly utilizing personal cars as their primary mode of transportation [29]. The number of vehicles and vehicle kilometers traveled (VKT) by different types may significantly influence vehicular emissions [30].

Remark: Average VKT values for motorcycles (MC), passenger cars (PC), vans, pick-ups, personal motorcycles (PMC), taxis, and buses were obtained from [26], the Pollution Control Department (PCD) database, and survey data collected in this study. Average VKT values for trucks were based on [26,27].

The average vehicle kilometers traveled (VKT) is represented in gray boxes, whereas the total VKT, expressed in million kilometers, is calculated by multiplying the number of registered vehicles by their corresponding average VKT.

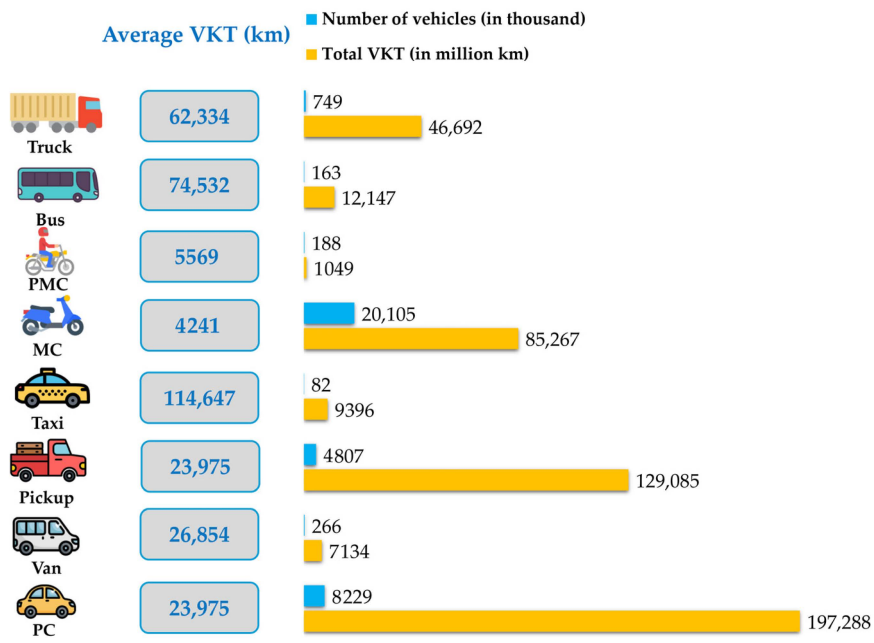


Figure 5. Estimated vehicle kilometers traveled (VKT) by vehicle type in Thailand, 2018.

2.3. Developing the Emission Factors with the International Vehicle Emissions (IVE) Model Emission Model

The inventory was established using the International Vehicle Emissions Model (IVE) version 2.0 to estimate the GHG emission inventory from mobile sources in Thailand for the base year of 2018. The University of California at Riverside developed the International Vehicle Emission (IVE) Model with funds provided by the U.S. Environmental Protection Agency (US EPA).

Emission factors significantly impact the emission inventory; therefore, various in-use vehicle emission tests should be conducted to assess whether the vehicles vary substantially from the default emission factors in the IVE Model. The emission prediction process of the IVE Model is initiated with a base emission rate, followed by the application of various correction factors to estimate pollution levels from different vehicle types. Regarding accurate emissions inventory development, the IVE Model is required, which consists of three parts: (1) emission rates of vehicles, including Base Emission Factor and Correction Factors; (2) location input data represents vehicle activity; and (3) fleet input data details the distribution of vehicles. We designed the IVE Model to quantify essential inputs using readily available local data and relevant existing information. Following the collection of this information, suitable mobile source inventories can be efficiently created and modified for the assessment of alternative scenarios [23,31,32].

The IVE Model's emission estimation process involves multiplying the base emission rate for each technology by the respective correction factors, which are specified for each vehicle technology, and the amount of vehicle travel to calculate the total emissions released. The model's calculation process is presented in Equation (1), which estimates the adjusted emission rate by multiplying the base emission rate (B) by a series of correction factors (K) to derive the adjusted emission rate (EF) for each vehicle type. Correction factors can be classified into multiple categories. The value of each correction factor depends on the entries selected in the Location File within the model [23].

$$EF_{(t)} = B_{(t)} \times K_{(1)(t)} \times K_{(2)(t)} \times \ldots..K_{(n)(t)} \quad (1)$$

Base emission rates are categorized into two types: those associated with running emissions and those related to starting emissions. The emission rate is adjusted based on the travel fraction and driving type associated with each technology. The travel fraction is data derived from the Fleet File within the model. The travel fraction ($f_{(dt)}$) for running emissions is expressed as a percentage of the time allocated to each vehicle-specific power (VSP) condition. To ensure proper weighting, the base emission rate ($EF_{(t)}$) must be converted from grams/km to grams/time by multiplying by the average velocity of the test procedure driving cycle prior to applying the fraction of time in each driving bin ($f_{(dt)}$). Subsequent to this calculation, the grams/time value can be converted to grams/distance by dividing by the average velocity of the cycle under evaluation ($\bar{U}_C$). This result represents the average running emissions in grams per kilometer for the fleet and driving patterns under analysis ($EF_{(running)}$) (Equation (2)). The units of emissions ($EF_{(start)}$) are consistently grams/start (Equation (3)). To calculate the overall emissions, multiply the total distance traveled by the total number of starts.

$$EF_{(running)} = \sum_t \left\{ f_{(t)} \times \sum_d [EF_{(t)} \times \bar{U}_{DC} \times f_{(dt)} \times K_{(dt)}] \right\} / \bar{U}_C \quad (2)$$

$$EF_{(start)} = \sum_t \left\{ f_{(t)} \times EF_{(t)} \times \sum_d [f_{(dt)} \times K_{(dt)}] \right\} \quad (3)$$

where

$EF_{(t)}$ = Adjusted emission rate for each vehicle type and technology, expressed as grams per start (g/start) or grams per kilometer (g/km)

$B_{(t)}$ = Base emission rate for each vehicle type and technology, expressed as (start (g/start) or running (g/km))

$K_{(1,2,..n)(t)}$ = Series of correction factors specific to each vehicle type and technology

$f_{(t)}$ = Fraction of travel by a specific technology

$f_{(dt)}$ = Fraction of time of each type of driving or fraction of soaks by a specific technology

$\bar{U}_{DC}$ = Average velocity of the test procedure driving cycle (a constant value in km/h)

$\bar{U}_C$ = Average velocity derived from the specified driving cycle, as provided by the user in the location file (km/h)

Accurate emissions estimation for an area requires the collection of data on driving behaviors and local environmental factors. The acquired information is then entered into the IVE location file, which includes details about the region's driving behaviors. This database includes information about driving frequency and characteristics, as well as speed and acceleration profiles. Tables 1 and 2 provide the details of fleet file information, and base adjustment file information, respectively. These files represent key aspects of vehicle emissions modeling. The following summarizes the standard procedure for data entry in this study.

Table 1. Thailand's vehicle fleet characteristics used as input for GHG emissions estimation with the IVE model, 2018.

Vehicle Type	Fuel Type	Fuel Type Contribution (%)	Engine Technology		VKT (km)
			Air/Fuel Control	Exhaust	
PC	Gasoline	60.48	FI/Carburetor	Euro 1–4/ 3 Way	<79,000
	Diesel	27.74			80,000–16,1000
	NGV-gasoline	1.97			>161,000
	LPG-gasoline	8.43			
	Hybrid	1.18			

Table 1. *Cont.*

Vehicle Type	Fuel Type	Fuel Type Contribution (%)	Engine Technology		VKT (km)
			Air/Fuel Control	Exhaust	
Van	Gasoline Diesel NGV-gasoline LPG-gasoline	7.12 84.57 2.73 4.32	FI/Carburetor	Euro 1–4/ 3 Way	<79,000 80,000–16,1000 >161,000
Pickup	Gasoline Diesel NGV LPG	2.83 93.94 0.72 2.06	FI/Carburetor	Euro 1–3/ 3 Way	<79,000 80,000–16,1000 >161,000
Taxi	Gasoline Diesel NGV-gasoline LPG-gasoline Hybrid	1.38 0.69 70.81 26.23 0.66	FI/Carburetor	Euro 3–4/ 3 Way	<79,000 80,000–16,1000 >161,000
MC	Gasoline	99.98	2 cycle, 4 cycle/FI	Catalyst	<25,000 25,000–50,000 >50,000
PMC	Gasoline	100.00	2 cycle, 4 cycle/FI	Catalyst	<25,000 25,000–50,000 >50,000
Bus	Gasoline Diesel NGV LPG	2.91 75.14 18.86 2.54	FI/Carburetor	Euro 1–2/ 3 Way/EGR	<79,000 80,000–16,1000 >161,000
Truck	Diesel NGV	83.74 2.11	FI/Carburetor	Euro 2–3/ 3 Way/EGR	<79,000 80,000–16,1000 >161,000

Remark: EGR = Exhaust Gas Recirculation; FI = Fuel Injections; NGV = Natural Gas for Vehicle; LPG = Liquefied Petroleum Gas.

Table 2. Input parameters for base adjustment in Thailand's application of the IVE Model.

Vehicle Type	VKT (km)	Engine Technology	Fuel Type
MC	<79,000 80,000–161,000 >161,000	4 cycle/Catalyst	Gasoline
PC	<79,000	Euro 2	Gasoline
	<79,000	Euro 3	
	<79,000 80,000–161,000 >161,000	Euro 4	
	>161,000	3 Way	NGV
Bus	>161,000	Euro 2	Diesel
Truck	>161,000	Euro 2	Diesel
Pickup	<79,000 80,000–161,000 >161,000	Euro 2–4	Diesel

Table 2. *Cont.*

Vehicle Type	VKT (km)	Engine Technology	Fuel Type
Van	<79,000 80,000–161,000 >161,000	Euro 2–4	Diesel

Location File

The Location File Input includes data related to ambient conditions and driving behavior, which is manually entered into the model. This study includes geographic conditions characterized by an average ambient temperature of 28.1 °C, and relative humidity of 76%. This study employed various driving cycles: light duty gasoline (LDG) for passenger cars and taxis at an average speed of 33.5 km/h, light duty diesel (LDD) for vans and pickups averaging 35.3 km/h, moped cycles for motorcycles and mopeds at 33.5 km/h, and heavy duty (HDV) for buses and trucks with an average speed of 23.4 km/h. The fuel standard was defined in accordance with the Euro 4 standard.

Fleet File

Fleet File Input is the core dataset describing the vehicle fleet structure. The input consists of the distribution of vehicle types, fuel types, emission control technologies, vehicle age distribution, and average annual vehicle kilometers traveled (VKT). This study considers fleet characteristics, covering passenger cars, vans, pickups, taxis, motorcycles, public motorcycles, buses, and trucks (Table 1). Each category encompasses variations in fuel types, including gasoline, diesel, natural gas vehicles (NGV), liquefied petroleum gas (LPG), and hybrid options. Furthermore, it utilizes various engine technologies, including fuel injections (FI), carburetors, and, particularly for motorcycles, 2-cycle or 4-cycle engines. Vehicles are equipped with air/fuel control and exhaust technologies like Euro emission standards, including Euro emission standards (from Euro 1 to Euro 4), three-way catalysts, and Exhaust Gas Recirculation (EGR). The emission standards for light- and heavy-duty vehicles are categorized from Euro 1 to Euro 4, with specific classifications: Euro 3–4 for taxis, Euro 1–3 for pickups, Euro 1–2 for buses, and Euro 2–3 for trucks. In this model, all vehicle types are categorized as medium-sized. Vehicle kilometers traveled (VKT) are classified into three categories: less than 79,000 km, between 80,000 and 161,000 km, and greater than 161,000 km for most vehicles. Motorcycles and PMCs exhibit lower VKT thresholds of less than 25,000 km, 25,000 to 50,000 km, and greater than 50,000 km. This classification supports emissions modeling by incorporating various engine and fuel combinations reflective of the Thai vehicle fleet.

Base Adjustment

Base Adjustment File Input allows for modification of default emission factors or engine performance parameters. The adjustment factors for GHG emissions in this study utilize the available local emission database. The IVE model utilizes baseline emission rates for running and start emissions associated with each vehicle technology. Base emissions are derived from dynamometer testing conducted on a specific cycle under standard conditions. This study developed the baseline emission factors of vehicles through chassis dynamometer testing, following closely to regulatory standards, including the Thai Industrial Standard (TIS 2560–2554) [33,34]. The measurement of vehicle emissions was conducted in vehicle laboratories and subsequently integrated with the existing emission database sourced from the Automotive Emission Laboratory (AEL), under the Pollution Control Department. This study employed the Bangkok driving cycle developed by the Pollution Control Department, which is considered the most suitable for motor vehicles used in Thailand. The

emission database records exhaust emissions from motor vehicles, including CO_2 and CH_4, categorized by technology and vehicle kilometers traveled (VKT). The database served as input parameters for the IVE model to estimate the adjusted emission rate, as summarized in Table 2.

The correction process in the IVE model involves the adjustment of base emission rates through functions that consider local environmental, fuel, and operational conditions. Essential inputs, including vehicle technologies, fuel properties, and vehicle kilometers traveled (VKT), are provided via the Base Adjustment and Fleet Files. The model utilizes multiplicative correction factors on these inputs, resulting in emission factors that more precisely reflect local driving conditions. This study calculated base adjustment ratios for each pollutant by comparing measured emission values with outputs from the IVE model. The ratios were utilized to refine the model's emission factors, resulting in more accurate and locally representative estimates.

2.4. Estimation of Greenhouse Gas Emissions from Road Transport

The methodologies and tools utilized for the GHG emission inventory complied with the 2006 IPCC Guidelines. Emissions from road transport can be estimated using two independent datasets: fuel consumption and vehicle kilometers traveled (VKT). Emissions may be estimated based on fuel consumption, indicated by fuel consumption, or by the distance traveled by vehicles. The fuel sold approach is suitable for CO_2, while the subsequent method (distance traveled by vehicle type and road type) is suitable for CH_4 and N_2O [35].

This study estimated greenhouse gas emissions from the road transport sector in Thailand utilizing the Tier 3 approach (Equation (4)). The selection of the estimation method was determined by the availability and quality of data, as guided by the decision tree. The Tier 3 approach necessitates comprehensive, country-specific data to produce activity-based emission factors for vehicle subcategories and may incorporate national models. It calculates emissions by multiplying emission factors with vehicle activity levels, including vehicle kilometers traveled (VKT), for each vehicle sub-category and road type. Vehicle subcategories are categorized based on type, age, and emissions control technology.

The equation for calculating greenhouse gas emissions is

$$Em_i = \sum_{a,b,c,d} (VKT_{a,b,c,d} \times EF_{a,b,c,d}) + \sum_{a,b,c,d} (C_{a,b,c,d}) \quad (4)$$

where

Em_i = emission of GHG i (kg)

$EF_{a,b,c,d}$ = emission factor (kg/km)

$VKT_{a,b,c,d}$ = vehicle kilometers traveled (VKT) during the thermally stabilized engine operation phase for a specific mobile source activity (km)

$C_{a,b,c,d}$ = emissions during warm-up phase (cold start) (kg)

a = fuel type (e.g., diesel, gasoline, natural gas, LPG)

b = vehicle type

c = emission control technology (e.g., uncontrolled, catalytic converter, etc.)

d = operating conditions (e.g., urban or rural road type, climate, or other environmental factors)

The emission estimation methodology utilized in this analysis relies on several fundamental assumptions to maintain alignment with the Thai transportation framework. Firstly, data regarding vehicle characteristics were obtained from nationally published databases and the relevant literature. They provide details on the number of vehicles, fuel types, vehicle ages, vehicle kilometers traveled (VKT) categorized by vehicle type. It was presumed that VKT would rise in proportion to the increase in vehicle ownership under a business-as-usual (BAU) scenario. Secondly, fuel types were specified according

to vehicle category and engine technology. Thirdly, scenarios for technology adoption, including the integration of electric vehicles (EVs), the use of natural gas vehicles (NGVs), and compliance with Euro 5 standards, were developed in accordance with governmental policy objectives and anticipated market trends. Additionally, it was assumed that older vehicles, particularly those over 15 years old, would be gradually retired in line with goals for fleet modernization. These assumptions create a solid framework for estimating emissions across various mitigation scenarios, reflecting both existing trends and future policy aspirations.

The utilization of multi-variable optimization methods, as illustrated by Cao et al. [36], supports the methodological framework of this research by highlighting the importance of incorporating vehicle characteristics, fuel type standard, and technology adoption factors into emission estimation models. Their results concerning energy efficiency further emphasize the significance of integrating system-level performance metrics when simulating actual emissions across various mitigation scenarios.

The global warming potential (GWP) conversion factors quantified greenhouse gas (GHG) emissions in terms of carbon dioxide equivalent units (CO_2eq). This study converted CH_4 and N_2O into CO_2-equivalent emissions using the Global Warming Potential (GWP) from the IPCC's Fifth Assessment Report (AR5) [37]. The application of GWP is based on the impact of GHGs over a 100-year time horizon relative to CO_2. The AR5 report provides GWP values of 1, 28, and 265 for CO_2, CH_4, and N_2O, respectively. The greenhouse gas emission inventory was derived from the emissions produced by each vehicle category. A comprehensive description of this approach is available in our earlier publication [38].

2.5. Assessing Future Trends in Greenhouse Gas Emissions Based on the Baseline Scenario and Different Mitigation Strategies

Projections regarding the total number of registered vehicles in Thailand were conducted to assess greenhouse gas emissions under various measures. To estimate the number of vehicles in Thailand from 2024 to 2030, it was necessary to initiate mobility prediction. The growth rates of new vehicle registrations for the period 2024 to 2030 were calculated by averaging historical data from 2010 to 2023. Buses demonstrated the highest growth rate at 8.34%, followed by passenger cars at 5.13%, trucks at 4.48%, vans at 1.80%, and motorcycles at 0.46%, respectively. The recorded growth rates for pickups, public motorcycles (PMCs), and taxis were 0.36%, 25.11%, and 25.83%, respectively. The projected growth rates of new vehicle registrations for pickups and motorcycles from 2024 to 2030 were determined using constant growth rates. The future trends of greenhouse gas emissions from the baseline situation, or business-as-usual scenario, were evaluated for the period 2018–2030 and compared to reduction scenarios. In the BAU scenario, it was assumed that no actions would affect the long-term trends of transport and that none of the mitigation options would be implemented from 2018 to 2030.

Mitigating climate change involves implementing strategies that reduce or prevent greenhouse gas emissions resulting from anthropogenic activities. Thailand's 2nd Updated Nationally Determined Contribution (NDC) outlines the country's goal to reduce greenhouse gas emissions by 30 percent from the projected business-as-usual (BAU) level by 2030. The Thai government establishes policies designed to decrease greenhouse gas emissions through various initiatives, including the promotion of electrification in all transport modes, enhancement of energy efficiency, adoption of alternative technologies, transition to renewable energy sources, and encouragement of sustainable urban transportation solutions. Biofuel serves as a critical component to be adopted in the transport sector as outlined in the AEDP2015 plan [16]. The targets for EV adoption in Thailand pertain exclusively to new vehicle registrations, rather than the existing vehicle fleet. Alternative

mitigation actions were analyzed for greenhouse gas emission reduction based on various scenarios, including:

(1) Motorcycle (MC) scenarios: transitioning 50% and 100% of new MCs to electric motorcycles (EMs).
(2) Passenger car (PC) scenarios: transitioning 50% and 100% of new PCs to electric vehicles (EVs) and phasing out PCs older than 15 years.
(3) Pickup scenarios: transitioning 50% and 100% of new pickups to electric vehicles (EVs) and phasing out pickups older than 15 years.
(4) Truck scenarios:
    (1) Transitioning new trucks to natural gas vehicles (NGVs) by utilizing compressed natural gas (CNG) at 50% and 100%, while phasing out trucks older than 15 years.
    (2) Transitioning new trucks to Euro 5 diesel trucks by 50% and 100%, while phasing out trucks older than 15 years.
(5) Integrated scenarios.

3. Results and Discussion

3.1. Greenhouse Gas Emission Factors

Table 3 presents the GHG emission factors for all vehicle categories in Thailand. These country-specific, technology-based emission factors are expressed as two emission values: emissions per traveled distance or running emissions (g/km) and start emissions (g/start). The findings from the IVE Model demonstrate that CO_2 shows the highest emission factors across all vehicle types in Thailand, followed by CH_4 and N_2O, respectively.

Table 3. Greenhouse gas emission factors categorized by vehicle type in Thailand (base year 2018).

Vehicle Type	CO_2		CH_4		N_2O	
	g/Start	g/km	g/Start	g/km	g/Start	g/km
PC	66.1607	309.4691	0.6446	0.5189	0.0409	0.0146
Van	104.0682	245.4869	0.4870	0.4160	0.0296	0.0129
Pickup	110.1494	234.5232	0.1462	0.1220	0.0264	0.0116
Taxi	35.4943	267.1711	8.5556	11.5247	0.0367	0.0290
MC	22.0326	43.2838	3.3530	1.0562	0.0033	N/A
PMC	26.5470	48.9357	10.9990	1.1636	0.0027	N/A
Bus	84.0842	707.3013	0.0462	0.4077	0.0244	0.0217
Truck	77.5590	548.4389	0.0090	0.0806	0.0665	0.0611

N/A = not applicable.

The CO_2 emission factors for start emissions ranged from 22.03 to 110.15 g/start. Pickups have the highest values, followed by vans, buses, trucks, PCs, and taxis, whereas MCs and PMCs demonstrate lower emission factors, respectively. The CO_2 emission factor for running emissions per distance (g/km) was determined to range from 43.28 to 707.30 g/km. Buses emitted the highest levels of CO_2, followed by trucks, PCs, taxis, vans, and pickups, whereas PMCs and MCs had lower emission factors. The higher CO_2 emission factors for buses may be attributed to the significant proportion of diesel-fueled buses, characterized by high carbon content in Thailand. Furthermore, older buses continue to be used in Thailand, potentially resulting in lower energy efficiency.

The country-specific, technology-based CO_2 emission factors (EFs) estimated in this study for the base year 2018 demonstrate notable differences when compared to the previous literature and official reports. Pickups exhibited a significantly lower average EF (234.52 g/km) compared to 919.6 g/km reported by Nilrit et al. [39]. Trucks showed an average EF of 548.44 g/km, which aligns with the range reported by the

Office of Transport and Traffic Policy and Planning (OTP) for diesel B7-fueled trucks (369.10–632.90 g/km) [40]. Passenger cars presented a higher EF (309.47 g/km) than prior studies (153.8 g/km) from Nilrit et al. [39]. Buses recorded a moderate EF (707.30 g/km), which is slightly below the upper range reported by cited by the OTP for diesel B7-fueled buses (75.75–808.10 g/km) [40]. Motorcycles and public motorcycles showed relatively lower CO_2 EFs (43.28 and 48.94 g/km, respectively) than prior studies (65–85 g/km) from Nilrit et al. [39]. Vans showed an average EF of 245.48 g/km, which is consistent with values from Nilrit and Sampanpanish (231.9–338.1 g/km) [41]. Taxis displayed EF of 267.17 g/km, respectively, which is slightly above international ranges (180–220 g/km) [42].

Diesel vehicles showed higher average CO_2 emissions compared to gasoline vehicles [42]. The average CO_2 emissions of diesel vehicles were higher relative to the average CO_2 emissions of petrol vehicles [42]. This finding is consistent with the fact that heavy-duty vehicles in Thailand are mainly diesel, with few emission controls; therefore, the CO_2 emission factors for heavy-duty vehicles are much higher than for light-duty vehicles. Nilrit et al. [43] found that new MCs showed higher CO_2 emissions compared to older models, as the advanced engine technology enables complete fuel combustion.

A significant quantity of CO_2 is emitted during travel or running in contrast to start-up. At start-up, particularly during a cold start (soak duration >12 h), the engine temperature is low, and fuel condensation forms on the inner surface of the cylinder, causing it to operate in rich mode (high fuel-to-air ratio). This leads to incomplete combustion of the fuel [44]. Furthermore, the catalyst takes longer to reach working temperature during the start-up time. However, during driving conditions, fuel is burned more completely, emitting CO_2 into the atmosphere together with other emissions.

The CH_4 emission factors for start emissions ranged from 0.0090 to 10.9990 g/start, while for running emissions, they ranged from 0.0806 to 11.5247 g/km. The findings indicated that taxis had the highest emission factor for CH_4. The use of NGV and LPG as alternative fuels in taxis in Thailand may account for this phenomenon. Methane is emitted during the incomplete combustion of fuel and is linked to natural gas engines [39]. Natural gas vehicle (NGV) fuel primarily consists of methane (CH_4), while liquefied petroleum gas (LPG) is mainly composed of butane and propane. In 2018, the taxi fleet consisted mainly of CNG petrol (70.81%) and CNG LPG (26.23%).

The CH_4 emission factors obtained in this study are generally higher than those reported in European datasets [42], particularly for passenger cars (0.5189 g/km) and taxis (11.5247 g/km). Nilrit et al. [45] indicates that NGV taxis emitted the highest CH_4 at all driving speeds, with an average emission of 1.33 g/km, higher than that from the LPG taxis. The elevated taxi emissions may be attributed to prolonged idling, alternative fuel use (e.g., LPG/CNG), and aging engines. PMCs and MCs displayed elevated CH_4 emission factors relative to other vehicle categories. Similarly, MCs and PMCs recorded EFs of CH_4 above international averages [42], reflecting urban traffic conditions and the continued use of two-stroke engines.

The previous study indicated that vehicles fueled with gasoline and lubricant oil (two-stroke mopeds) emitted significantly higher levels of CH_4 compared to those fueled only with gasoline and diesel. Additionally, vehicles fueled only with petrol, including four-stroke mopeds, and light- to high-performance motorcycles, showed considerably higher CH_4 emissions than their diesel-fueled counterparts. The higher CH_4 emissions from mopeds can be attributed to the less sophisticated after-treatment systems installed in these vehicles relative to other categories of petrol vehicles. CH_4 emissions are significantly associated with the cold start of vehicles, with unburned hydrocarbons. Furthermore, fuel containing a high concentration of ethanol might produce more water accumulation on the catalyst surface, thereby affecting the oxidation of CH_4.

The results for N_2O emissions indicated that start emissions varied from 0.0027 to 0.0665 g/start, while running emissions ranged from 0.0116 to 0.0611 g/km. The findings indicated that trucks showed the highest N_2O emission factor. The emission of N_2O during start-up is greater than that during running. A research investigation on the relationship between fuel/engine technology and GHG tailpipe emissions from L-category vehicles (mopeds, motorcycles, and quads) revealed that gasoline-fueled vehicles emitted significantly higher N_2O emissions compared to those using a combination of gasoline and lubricant oil [42]. This trend can be attributed to the presence of three-way catalysts (TWCs) in gasoline-fueled vehicles. Diesel-fueled LDVs showed significantly larger N_2O emissions than gasoline-fueled LDVs. Nitrous oxide generated from transportation occurs through both combustion and catalytic processes. Nitrous oxide (N_2O) is produced from the gas-phase reactions of nitric oxide (NO) with hydrogen cyanide (HCN) or ammonia (NH_3) during fuel combustion. Modern catalytic converters designed for the removal of NO_x, CO, and hydrocarbons are related to N_2O emissions.

The findings highlight the variability of emission factors among different vehicle types and contexts. The discrepancies in CO_2 emission factors between this study and literature are mostly attributed to the differences in vehicle technology, driving pattern, and composition of the fleet. Lower emissions factors in specific vehicle types indicate advancements in engine efficiency and fuel economy, whereas higher values in passenger cars and taxis may be attributed to urban congestion and the increasing number of older vehicles. Localized activity data, such as vehicle kilometers traveled (VKT), fuel quality, and vehicle age, enhanced the precision of context-specific estimates. The necessity for continuous updates utilizing real-world, country-specific data is underscored to ensure that emission inventories effectively support transport emission mitigation strategies.

The country-specific emission factors derived from the IVE model were utilized to estimate the total greenhouse gas emissions from the road transportation sector in Thailand. These greenhouse gas emission factors provide a more accurate representation of tailpipe emissions. This study presents GHG emission factors categorized by vehicle type and engine technology, as detailed in the Supplementary Information (Table S1).

3.2. Greenhouse Gas Emission Inventory of the Road Transport Sector in the Base Year 2018

The GHG emission inventory of road transport in the base year, 2018, is shown in Table 4. The total CO_2 emissions from the road transport sector were the highest, amounting to 21,128.75 Gg, followed by CH_4 and N_2O emissions, respectively. The greenhouse gas (GHG) emission inventory for the road transport sector in the base year 2018 is presented in Table 4. The impact of the emissions from the different vehicle types existing within the fleets in Thailand have been studied in order to understand the general emissions. The emissions contributions of each type of vehicle are shown in Figure.

The CO_2 emissions for each vehicle category varied from 10.46 to 5762.97 Gg/year. Pickups accounted for approximately 27.28% of total CO_2 emissions, followed by trucks at 22.97%, passenger cars at 20.81%, and buses at 19.03%. PMC, MC, van, and taxi emissions constituted less than the previously stated vehicles, representing 9.91% of total CO_2 emissions. The majority of CO_2 emissions are emitted during driving. Light vehicles (passenger cars, vans, pickups, and taxis) accounted for around 52.01% of CO_2 emissions, whereas trucks and buses contributed 42.01%, and motorcycles provided 5.98%. This result indicates that light-duty vehicles were the main sources of vehicular CO_2 in Thailand.

The total emission of CH_4 is estimated that the total CH_4 emissions are 88.16 Gg. GHGs from different vehicle categories ranged from 0.04 to 47.86 Gg/year. Taxis were the largest contributors, contributing 54.28% of total CH_4 emissions, followed by motorcycles at 36.09% and passenger cars at 7.97%. Other vehicles emitted lower CH_4 emissions,

representing 1.65% of the overall CH_4 emissions. The majority of CH_4 emissions are also emitted during driving.

Table 4. Emission inventory of GHGs from the road transport sector in the base year 2018.

Vehicle Type	CO_2 (Gg/Year)			CH_4 (Gg/Year)			N_2O (Gg/Year)			CO_2eq (Gg/Year)
	Start	Running	Total	Start	Running	Total	Start	Running	Total	
PC	4.09×10^{-2}	4397.67	4397.71	2.27×10^{-4}	7.03	7.03	3.05×10^{-5}	0.24	0.24	4658.44
Van	5.32×10^{-3}	259.78	259.78	1.69×10^{-6}	0.04	0.04	1.06×10^{-6}	0.01	0.01	264.25
Pickup	1.20×10^{-1}	5762.85	5762.97	3.20×10^{-6}	0.07	0.07	2.10×10^{-5}	0.25	0.25	5830.62
Taxi	9.23×10^{-4}	569.50	569.50	2.97×10^{-4}	47.86	47.86	1.03×10^{-6}	0.09	0.09	1934.38
MC	1.68×10^{-1}	1253.12	1253.29	1.38×10^{-2}	31.80	31.82	2.83×10^{-5}	0.00	2.83×10^{-5}	2144.22
PMC	1.21×10^{-3}	10.45	10.46	4.41×10^{-4}	0.26	0.26	1.37×10^{-7}	0.00	1.37×10^{-7}	17.86
Bus	6.10×10^{-3}	4021.64	4021.65	9.84×10^{-7}	0.64	0.64	8.54×10^{-7}	0.05	0.05	4053.00
Truck	1.09×10^{-2}	4853.37	4853.38	7.76×10^{-7}	0.44	0.44	9.54×10^{-6}	0.55	0.55	5011.25

Remark: The AR5 report's GWP values for CO_2, CH_4, and N_2O for a 100-year time horizon are 1, 28, and 265, respectively.

The calculated vehicle emissions of nitrous oxide (N_2O) amounted to 1.20 Gg. Emissions of various transportation vehicle types ranged between 1.37×10^{-7} and 0.55 Gg/year. Trucks were the most contributing group (45.98% of total N_2O emissions), followed by pickups (20.71%), passenger cars (20.17%), taxis (7.85%), buses (4.24%), and vans (1.05%). Emissions from other cars and light vehicles contributed 18.23% of total GHG emissions (Figure 6). The majority of N_2O emissions are released during driving, whereas the N_2O emissions from MCs and PMCs are associated with start-up.

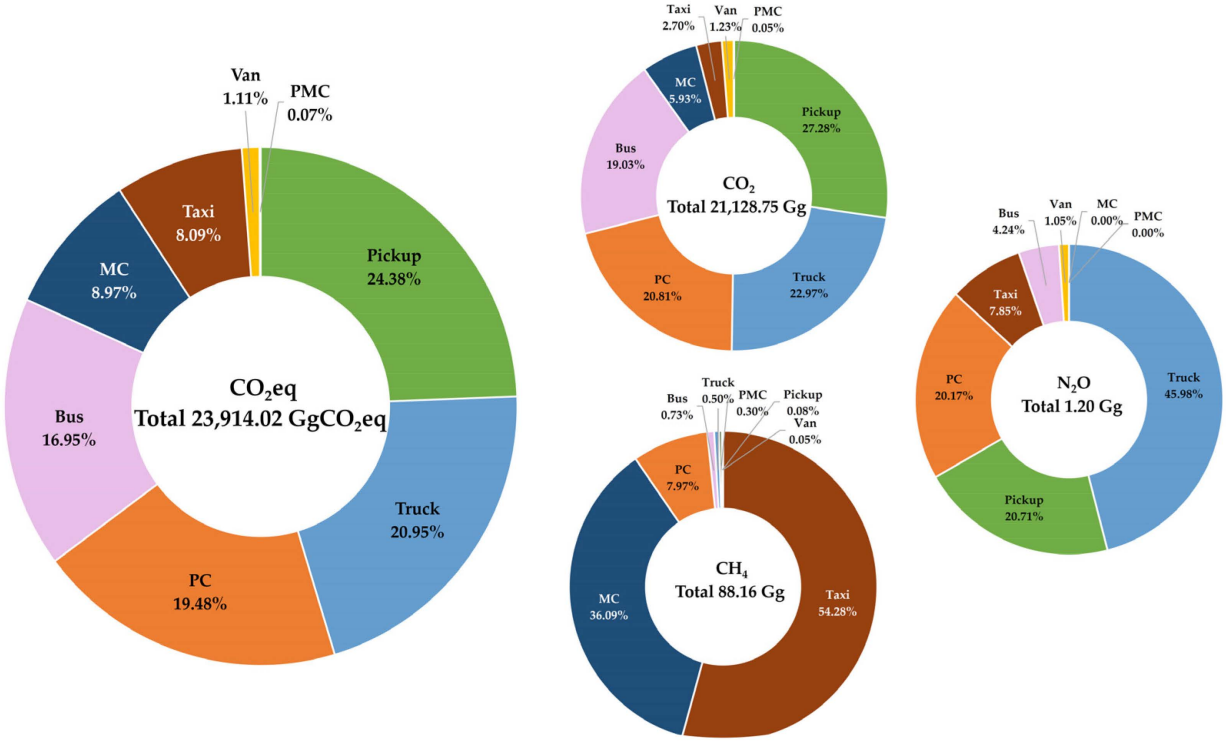


Figure 6. Emission share of Greenhouse gas (GHG) by vehicle type in Thailand, 2018.

In 2018, passenger cars and pickups constituted 40.39% of the vehicle population in Thailand. Although equipped with advanced emission control technologies, light-duty vehicles accounted for 48.09% of total CO_2 emissions and 40.88% of total N_2O emissions, corresponding to 66.87% of total vehicle kilometers traveled (VKT). Taxis represented 0.22% of the overall vehicle population; however, they contributed to 54.28% of total CH_4 emissions. Light-duty vehicles were the primary contributors to GHG emissions in

Thailand. Motorcycles comprised 52.81% of the vehicle population and were responsible for 25.33% of total CH_4 emissions and 5.79% of total CO_2 emissions. Trucks accounted for 2.84% of the total; nevertheless, they were responsible for 45.98% of overall N_2O emissions, due to a higher N_2O emission factor and the average travel distance of the vehicles. Nitrous oxide is an undesirable by-product of exhaust gases released from systems for treating diesel engine emissions [46]. Approximately 76.49% of trucks in Thailand utilize diesel fuel, while 40% of used trucks exceed 20 years in age.

According to the previously mentioned findings, restricting the use of light-duty vehicles would be helpful in decreasing CO_2 emissions. Enhancing emission control technology for vehicles is essential for reducing greenhouse gas and air pollutant emissions. Furthermore, mandating the discontinuation of non-electric mopeds will effectively diminish both greenhouse gas and air pollutant emissions in Thailand [45].

According to the 100-year Global Warming Potential (GWP) of these GHGs, the amount of GHG emissions in road transport is quantified in units of Gigagrams of carbon dioxide equivalent ($GgCO_2eq$). The findings revealed that the overall greenhouse gas emissions from the road transport sector in 2018 amounted to 23,914.02 $GgCO_2eq$. Carbon dioxide is the primary catalyst of global warming. Pickups were the predominant contributors to greenhouse gas emissions from road transport, followed by trucks, passenger cars, and buses, representing 24.38%, 20.96%, 19.48%, and 16.95% of total emissions, respectively. The findings of this study underscore the importance of focusing on high-use vehicle types in prospective emission-control policy.

3.3. Projections of the Total Number of Registered Vehicles in Thailand

The accumulated number of vehicles registered in Thailand with their projections are shown in Figure 7. Results showed that the total number of vehicles is expected to increase. The total number of accumulated registered vehicles is projected to reach 51 million by 2030. Motorcycles, vans, and passenger cars are experiencing significant growth in the future due to rising new vehicle registrations, whereas taxis and public motorcycles are anticipated to decline consistently from 2024 to 2030. Other vehicle categories are projected to remain steady from 2024 to 2030.

Thailand has implemented the Alternative Energy Development Plan (2015–2036) with the objective of decreasing its dependence on conventional resources [47]. Consequently, the introduction of new vehicle models has resulted in swift improvements in the fuel economy across certain categories, and the number of alternative fuel options has increased. Several new vehicle categories, including motorcycles, passenger cars, pickups, and buses, are being introduced to electric vehicles (EVs). Conversely, the quantity of petroleum, diesel, and flex-fuel vehicles (FFVs) is diminishing as the availability of alternative fuels expands. Additionally, many vehicle categories, including taxis and buses, are reducing or eliminating their dependence on fossil fuels. Due to their considerable time spent on the road and comparatively higher fuel consumption than alternative transportation modes. This has a significant effect on air quality, especially in urban areas. In that respect, the Thai government's initiative of support for electric public transportation is a remarkable solution that offers a cleaner and less polluting approach compared with conventional fossil fuel-driven cars and significantly contributes to abating air pollution [48].

The primary y-axis (left) indicates total figures for major categories (MC, PC, Pickup, and Truck), whereas the secondary y-axis (right) is designated for smaller categories (Van, Taxi, PMC, and Bus) to enhance visual clarity.

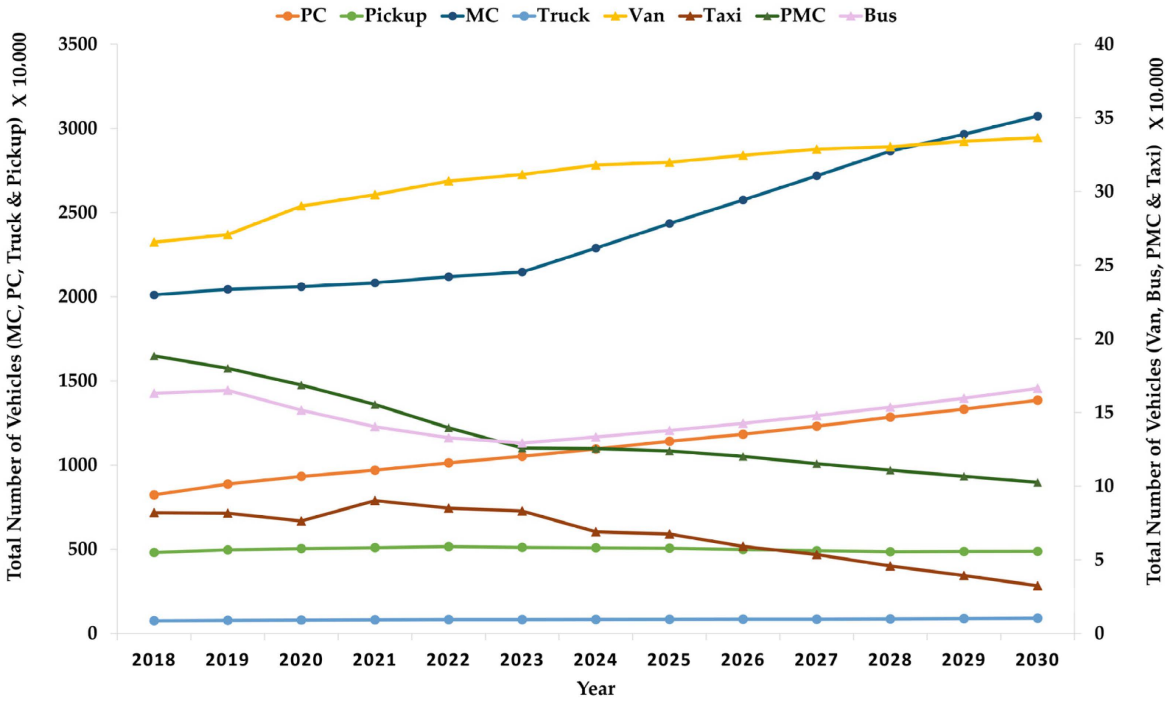


Figure 7. Projected number of registered vehicles by type in Thailand, 2018–2030.

3.4. Trends of GHG Emissions in the Road Transport Sector from 2018 to 2030 (BAU Scenario)

In the business-as-usual (BAU) scenario, it is assumed that no measures are adopted to affect the long-term trends in transportation and no mitigation strategies are executed. The projection of GHG emissions is anticipated for the years 2018–2030.

Figure 8 illustrates that total greenhouse gas emissions in the road transport sector are expected to rise from 23,914 $GgCO_2eq$ in 2018 to 43,802 $GgCO_2eq$ in 2030, reflecting an average annual growth rate of 5.31%. The total greenhouse gas emissions, represented by the red line, are projected to increase from 23,914 $GgCO_2eq$ in 2018 to 43,802 $GgCO_2eq$ by 2030. By 2030, trucks were the largest contributors to GHG emissions, representing 34.38% of total emissions in the road transport sector. The latter was followed by passenger cars at 25.85%, pickups at 18.57%, and buses at 11.20%. Trucks, pickup trucks, and passenger cars would be the top three contributors to the total emissions during the forecast period because of their larger VKT and fleet shares. In the absence of immediate action, trends in greenhouse gas emissions are projected to increase beyond 2030. This trend presents a significant challenge to achieving the national goals of attaining carbon neutrality by 2050 and achieving net-zero greenhouse gas emissions by 2065. This highlights the necessity for the country to mitigate future emissions. Mitigation measures such as subsidies for clean transportation, support for renewable energy sources, promotion of electric vehicles, and enhancement of public transport can significantly reduce greenhouse gas emissions in the transportation sector [16,49,50]. Therefore, stringent greenhouse gas reduction strategies should be implemented in the transportation sector. Furthermore, pollution control policies and legislation could lead to climate co-benefits when they extend beyond end-of-pipe measures [38,51]. The results demonstrate the need for targeting these types of vehicles as part of an effective mitigation approach.

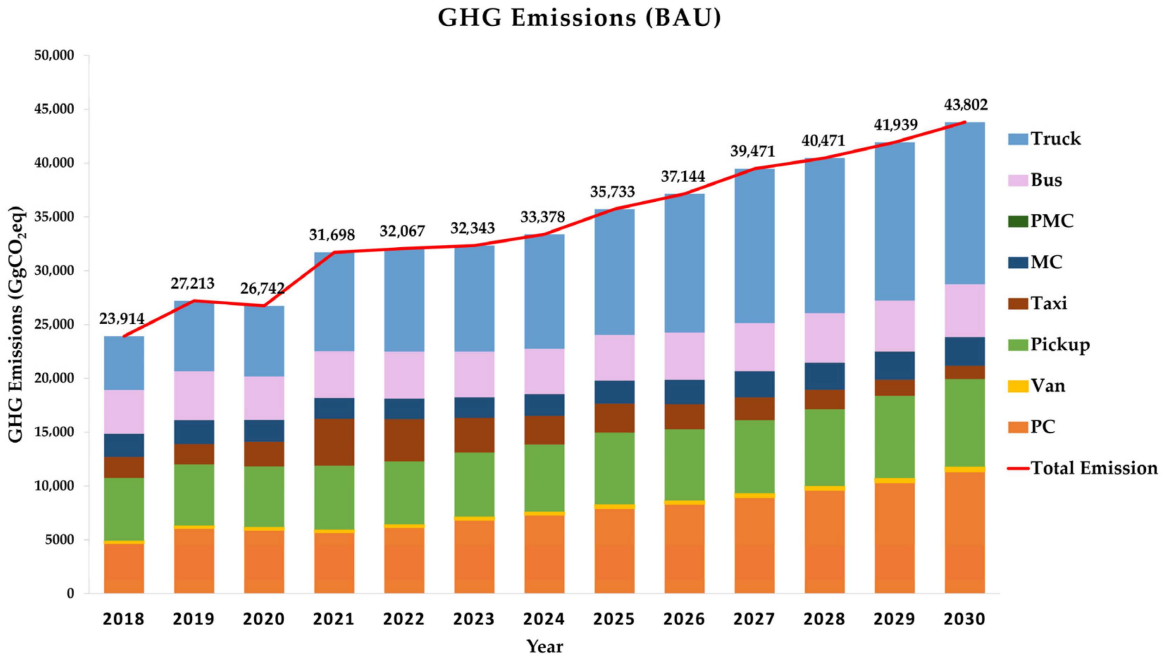


Figure 8. Projected greenhouse gas emissions by vehicle type in Thailand under the business-as-usual (BAU) scenario, 2018–2030.

3.5. Trends of GHG Emissions in the Road Transport Sector from the Alternative Mitigation Scenarios from 2024 to 2030

This analysis has examined alternatives for global mitigation, namely from the enhancement of energy efficiency and utilization of alternative energy. Increase in energy efficiency will be obtained by engine performance, road surface and behavioral improvements. There is a growing percentage of fuel-efficient vehicles being introduced in the market, from hybrid, plug-in hybrid, electric, up to the fuel cell electric vehicles (FCEVs) operating under fuel-cell technology. Electric vehicles (EVs) are a key part of the transition to a clean energy future. The transition to cleaner technologies, including EVs, remains a significant challenge within the transportation sector. Electric vehicles have the potential to decrease greenhouse gas emissions, and implementing relevant policies is crucial for promoting the adoption of these vehicles and achieving reductions in emissions [52,53]. Improvements in the efficiency of internal combustion engine (ICE) vehicles involve transitioning to EURO5 and EURO6 standards, promoting liquid biofuels, and eliminating petroleum subsidies [5,54]. The Thai government has committed to implementing the Euro 5 standard to regulate emissions from trucks, buses, pickup trucks, and small passenger cars powered by diesel and gasoline engines, thereby mitigating environmental impact in alignment with governmental policies. This is also in line with the national action plan on dust pollution control, which will come into force on 1 January 2024.

This paper assesses the potential of GHG reductions in the road transport sector under alternative mitigation scenarios. Figure 9 depicts the projected greenhouse gas (GHG) emissions from Thailand's road transport sector under various mitigation scenarios for the years 2018 to 2030. The particulars are described as follows:

1. Motorcycle (MC) scenarios

The Department of Land Transport's measures to transition from conventional gasoline to electric vehicles indicate that shifting new motorcycles to electric vehicles by 50% and 100% has the potential to decrease emissions relative to the business-as-usual scenario. The reduction in MC emissions resulting from the transition of new MCs to EMs by 50% and 100% decreased from 2662.43 $GgCO_2eq$ to 1644.51 and 1304.38 $GgCO_2eq$ in 2030,

respectively. This finding suggests that MC emissions from the use of EMs at 100% could potentially decrease by 20.25–52.66% between 2024 and 2030 compared to baseline emission, as shown in Figure 9a.

The total greenhouse gas emissions in the road transport sector, utilizing EMs at 50% and 100%, increased from 23,914.02 $GgCO_2eq$ in 2018 to 42,783.60 $GgCO_2eq$ and 42,443.47 $GgCO_2eq$ in 2030, respectively. The results showed an average annual reduction in greenhouse gas emissions of 1.67% and 2.64% compared to the business-as-usual scenario, respectively. Transitioning new motorcycles to 100% electric motorcycles by 2030 may lead to greenhouse gas emission reductions of approximately 1.22–3.26% from 2024 to 2030, relative to baseline emissions.

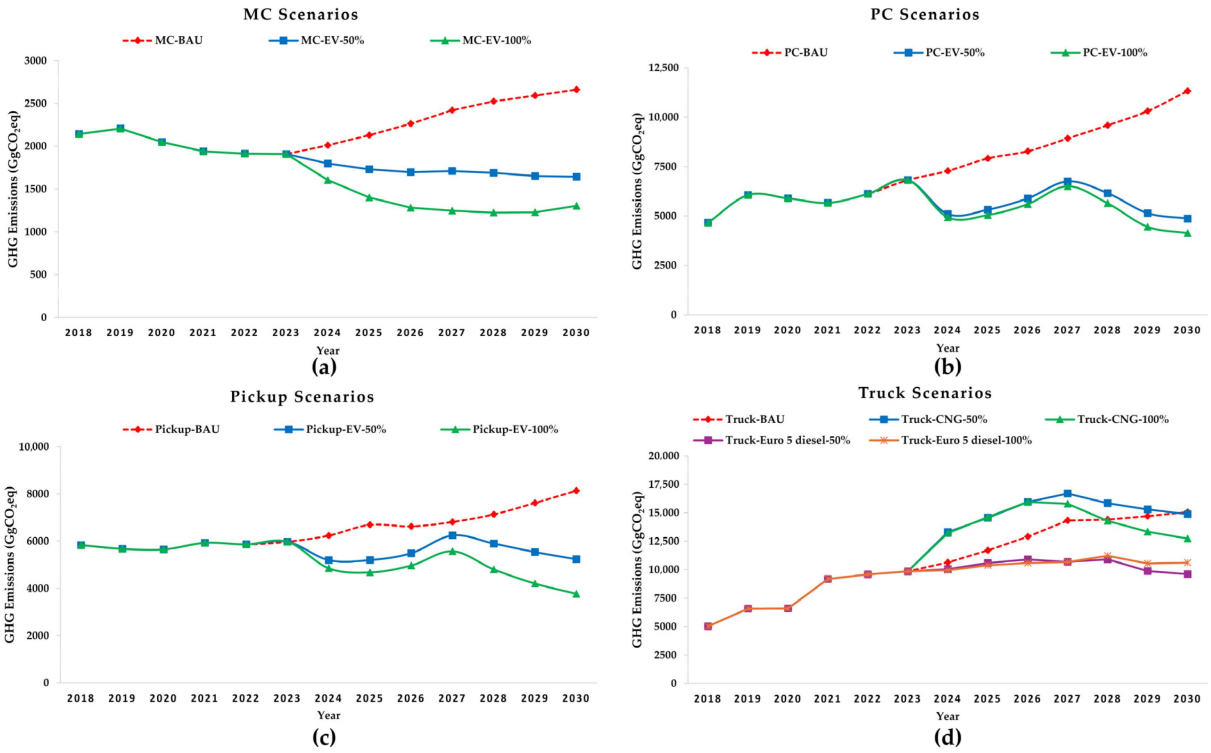


Figure 9. Comparative greenhouse gas emissions from road transport under mitigation scenarios in Thailand, 2018–2030. The scenarios are classified according to vehicle type: (**a**) Motorcycles (MC) with electrification levels of 50% and 100%; (**b**) passenger cars (PC) with electric vehicle (EV) penetration at 50% and 100%; (**c**) pickups with 50% and 100% EV adoption; and (**d**) trucks with technology upgrades, including compressed natural gas (CNG) and Euro 5 diesel, at substitution rates of 50% and 100%.

2. Passenger car (PC) scenarios

The Department of Land Transport has introduced measures to promote the transition to electric, plug-in hybrid electric, or hydrogen fuel cell vehicles, substituting conventional gasoline or diesel vehicles and restricting inefficient vehicle models. Scenarios for personal cars are considered by increasing the proportion of electric vehicles to 50% and 100% and phasing out personal cars older than 15 years. Results demonstrated a reduction in PC emissions compared to the business-as-usual scenario. The reduction in PC emissions resulting from a transition to EVs by 50% and 100% decreased from 11,323.07 $GgCO_2eq$ to 4869.04 and 4129.40 $GgCO_2eq$ in 2030, respectively. This finding suggests that utilizing EVs exclusively and phasing out PCs older than 15 years could lead to a potential reduction of 27.08–63.53% in PC emissions from 2024 to 2030, compared to a business-as-usual scenario, as shown in Figure 9b.

The total greenhouse gas emissions in the road transport sector, with the adoption of electric vehicles at 50% and 100%, and the elimination of passenger cars older than 15 years, have increased from 23,914.02 $GgCO_2eq$ in 2018 to 37,347.50 $GgCO_2eq$ and 36,607.86 $GgCO_2eq$ in 2030, respectively. The results indicated an average annual reduction in greenhouse gas emissions of 8.75% and 9.79% relative to the business-as-usual scenario, respectively. The analysis suggests that achieving a transition to 100% electric vehicles by 2030 could result in greenhouse gas emission reductions of approximately 6.12–16.42% from 2024 to 2030, compared to a business-as-usual scenario. Greenhouse gas emissions have dramatically risen since 2024; however, a decline is anticipated after 2027. The observed reduction may be attributed to a considerable percentage of vehicles between 8 and 15 years old that comply with Euro 4 standards and have exceeded 161,000 km in the distance traveled [55,56].

3. Pickup scenarios

Pickup scenarios are evaluated by transitioning 50% and 100% of new pickups to electric vehicles (EVs) and phasing out pickups that are older than 15 years. Results indicated a reduction in pickup emissions compared to the business-as-usual scenario. The reduction in pickup emissions resulting from a transition to electric vehicles (EVs) by 50% and 100% decreased from 8134.21 $GgCO_2eq$ to 5232.32 and 3768.53 $GgCO_2eq$ in 2030, respectively. This finding suggests that utilizing electric vehicles (EVs) for pickups and phasing out pickups older than 15 years could potentially decrease emissions by 18.22–53.67% from 2024 to 2030, compared to a business-as-usual scenario, as shown in Figure 9c.

The total greenhouse gas emissions in the road transport sector utilizing electric vehicles, with reductions of 50% and 100%, and the phasing out of pickups older than 15 years, have risen from 23,914.02 $GgCO_2eq$ in 2018 to 40,899.64 $GgCO_2eq$ and 39,435.85 $GgCO_2eq$ in 2030, respectively. The findings indicated an average annual reduction in greenhouse gas emissions of 3.77% and 5.89% relative to the business-as-usual scenario, respectively. The transition of all pickups to electric vehicles (EVs) could lead to a reduction in greenhouse gas emissions ranging from 3.14% to 9.97% between 2024 and 2030, relative to the business-as-usual scenario. A comparable trend was observed regarding emissions from PCs and pickups.

4. Truck scenarios

Two alternative mitigation measures are evaluated in truck scenarios. The results are presented below:

- Transition to Natural Gas Vehicles (NGVs) and phase out trucks that are older than 15 years.

Natural gas is utilized as an alternative fuel due to its relatively low carbon content relative to other fossil fuels. Compressed natural gas (CNG) is generated through the compression of conventional natural gas, primarily consisting of methane (CH_4) [57]. CNG is presently utilized as an alternative fuel for trucks, taxis, and buses, with a notable increase in its adoption. The negative effects of diesel and gasoline emissions have positioned CNG as a promising alternative fuel for road transportation. The Department of Land Transport in Thailand has promoted the adoption of clean energy and environmentally friendly alternative energy sources in trucks.

As a result of shifting new trucks to natural NGVs using CNG by 50% and 100% and phasing out of pickups older than 15 years, the truck emissions are expected to increase initially before declining after 2027. The amount of truck emissions decreased from 15,058.54 $GgCO_2eq$ to 14,876.91 $GgCO_2eq$ by using NGVs-CNG 50% and 12,725.93 $GgCO_2eq$ by using NGVs-CNG 100% in 2030, respectively. This finding demon-

strated that truck emissions using NGVs-CNG by 100% as well as eliminating the use of trucks older than 15 years could potentially reduce by 0.83–15.49% between 2028 and 2030 relative to the business-as-usual scenario, as shown in Figure 9d.

The overall GHG emissions in the road transport sector using NGVs-CNG scenarios and eliminating the use of old trucks have increased from 23,914.02 $GgCO_2eq$ in 2018 to 43,619.90 and 41,468.92 $GgCO_2eq$ in 2030 by using NGVs-CNG 50% and 100%, respectively. It was revealed that truck scenarios by shifting new trucks to NGVs-CNG by 100% could result in GHG emission reductions of about 0.30–5.33% between 2028 and 2030 compared to the business-as-usual scenario.

- Transition to Euro 5 Diesel Trucks and phase out trucks that are older than 15 years.

Thailand has officially adopted the Euro 5 standard for diesel fuel effective 1 January 2024. Euro 5 diesel fuel contributes to enhanced engine performance through the reduction in emissions, improvement of fuel efficiency, and extension of engine life [58]. This move aligns with the country's commitment to reducing air pollution and enhancing environmental quality.

Shifting new trucks to use Euro 5 diesel by 50% and 100%, along with the phasing out of trucks older than 15 years, indicated a reduction in trucks emissions compared to the BAU baseline. The reduction in truck emissions resulting from a transition to use Euro 5 diesel by 50% and 100% decreased from 15,058.54 $GgCO_2eq$ to 9597.90 and 10,607.02 $GgCO_2eq$ in 2030, respectively. This finding demonstrated that truck emissions using Euro 5 diesel by 50% as well as eliminating the use of trucks older than 15 years could potentially reduce by 5.55–36.26% between 2024 and 2030 relative to the business-as-usual scenario, as shown in Figure 9d.

The transition towards Euro 5 diesel vehicles at 50% and 100%, as well as phasing out of old trucks have resulted in a rise in the total greenhouse gas emissions in the road transport sector, from 23,914.02 $GgCO_2eq$ in 2018 to 38,340.89 $GgCO_2eq$ and 39,350.01 $GgCO_2eq$ in 2030. The results show that achieving a 50% and 100% penetration of new truck sales of Euro 5 diesel vehicle sales can result in average (calculations based on the comprehensive scenario) greenhouse gas emission reductions of 7.44% and 7.02%, respectively, compared to the business-as-usual scenario. The study demonstrates that the transition of 50% of new trucks to Euro 5 diesel and the elimination of trucks older than 15 years could reduce greenhouse gas emissions by 1.77–12.47% from 2024 to 2030 in comparison to the business-as-usual scenario.

Previous studies have shown that the promotion of alternative technologies in road transport, such as CNG and biofuels, along with improvements in vehicle energy efficiency, can significantly reduce energy-related greenhouse gas emissions [11,50]. Seo et al. [59] assessed the total greenhouse gas emissions and energy efficiency of compressed natural gas heavy-duty vehicles in Korea. Their result indicates that CNG-HDVs produce 6.3% lower emissions (in g/km) compared to diesel-HDVs of comparable weight. Consequently, substituting diesel vehicles with NGVs significantly decreases these emissions. CNG can reduce GHG emissions by up to 34% compared to diesel. However, CNG combustion may result in elevated levels of other air pollutants, including CO and NO_x [60]. Lajevardia et al. [61] indicated that CNG trucks emit 13–15% less CO_2 than comparable diesel trucks, depending on weight class and driving cycle. The results indicated that CO_2 reductions in heavy-duty trucks are primarily influenced by drivetrain technology, with operational conditions having a lesser impact. Furthermore, improving vehicle technology has the potential to decrease CO_2 emissions and fuel consumption [62].

5. Integrated scenarios

The findings suggest that adoption of a single mitigation option might not be enough to decrease the total GHG emissions in the road transport. As a result, integrated alternative scenarios were considered in order to compare impactful mitigation measures. Various alternative scenarios exist to mitigate greenhouse gas emissions associated with road transportation. Figure 10a illustrates that the implementation of the combined alternative scenarios results in a significant increase in GHG emissions since 2024, with a projected decrease anticipated after 2027. The total greenhouse gas emissions from the integrated scenarios of 50% switching (MC-EM-50%, PC-EV-50%, Pickup-EV-50%, and Truck-Euro 5 diesel-50%) increased from 23,914.02 $GgCO_2eq$ in 2018 to 27,967.04 $GgCO_2eq$ by 2030. The analysis of integrated scenarios involving 100% transitions (PC-EV-100%, MC-EM-100%, Pickup-EV-100%, and Truck-Euro 5 diesel-100%) indicated a consistent trend in total GHG emissions, rising from 23,914.02 $GgCO_2eq$ in 2018 to 26,432.61 $GgCO_2eq$ by 2030. The scenarios of 50% and 100% new vehicles adoption contribute to reducing GHG emissions by 36.15% and 39.65%, respectively, in 2030 relative to the BAU (Figure 10b).

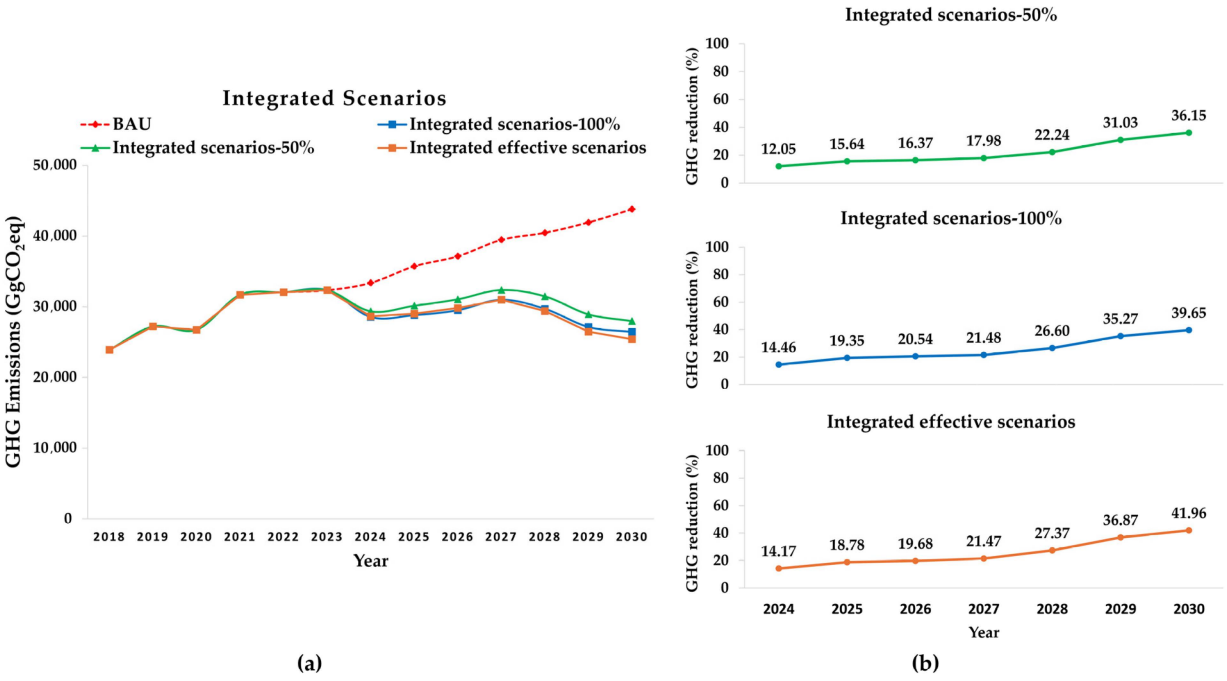


Figure 10. Projected Greenhouse Gas Emissions and Reduction Potentials under Integrated Mitigation Scenarios in Thailand's Road Transport Sector, 2018–2030: (**a**) Integrated scenario; (**b**) reduction potentials by integrated scenario. This figure illustrates projected greenhouse gas (GHG) emissions and mitigation potential under integrated mitigation scenarios for Thailand's road transport sector 2018–2030: (**a**) total GHG emissions under the Business-as-Usual (BAU) baseline incorporating three integrated mitigation scenarios: 50% implementation, 100% implementation, and the most effective scenario (**a**) combination of selected high-impact measures); and (**b**) percentage decrease in GHG emissions, 2024–2030 relative to BAU.

Furthermore, the implementation of integrated effective scenarios (PC-EV-100%, MC-EM-100%, Pickup-EV-100%, and Truck-Euro 5 diesel-50%) revealed an increase in overall GHG emissions in the road transport sector, rising from 23,914.02 $GgCO_2eq$ in 2018 to 25,423.48 $GgCO_2eq$ by 2030. This indicates that integrated effective scenarios may reduce GHG emissions by up to 41.96% in 2030 relative to a business-as-usual scenario, as illustrated in Figure 10b. The findings indicate that adopting an integrated approach that incorporates effective mitigation measures will contribute to the reduction in GHG emis-

sions. The results also emphasize a need for integrated policies across vehicle categories to meet climate change goals at the national level. Additional measures should be considered to further decrease overall GHG emissions.

The primary variables influencing emission levels can be categorized into travel-related, vehicle-related, driver-related, roadway-related, fuel type, and environmental variables [63]. Factors related to travel include vehicle kilometers traveled, speed, and engine operating modes. Vehicle emissions are also affected by factors such as gross vehicle weight (GVW), engine power, engine type, vehicle class, engine aftertreatment, engine maintenance, vehicle age, vehicle aerodynamics, and tire rolling resistance [64–66]. Failure to inspect the vehicle, particularly when it has traveled over a cumulative mileage of 161,000 km, may result in deterioration and an increase in greenhouse gas emissions. An increase in the number of new vehicles shifting to electric vehicles may lead to a reduction in greenhouse gas emissions. Greenhouse gas emissions from all motor vehicles have consistently increased, primarily due to older vehicles with high mileage producing greater emissions. An outdated engine with limited emissions reduction technology results in increased fuel consumption and more carbon emissions [55].

3.6. Discussion on Emission Reduction Potential

Several countries have successfully implemented policy and technology measures to reduce greenhouse gas (GHG) emissions from the transport sector. The European Union's CO_2 emission targets for light-duty vehicles envisage targets for 2030 as a 55% reduction (compared to 2021) and by 2035 there should be no CO_2 emissions from the new fleet of cars, effectively promoting the uptake of low-emission technologies such as hybridization and electrification. Supported by technology-neutral targets and the Worldwide Harmonized Light Vehicles Test Procedure (WLTP), these policy measures constitute an effective framework for the control of emissions [67,68]. In Norway, the combination of a suite of policy instruments including fiscal incentives, substantial expansion of the charging infrastructure, and strong government procurement support has combined to enable plug-in electric vehicles, particularly battery EVs, to reach 97% market share of new car registration in April 2025 [69]. The milestone proves that Norway is continuing to move in the right direction to phase out fossil-fuel car sales by 2025. To follow the same path, in Thailand's case, we would need the introduction of forward-looking CO_2 standards combined with higher fuel quality and much more aggressive regulation. While there are differences in structure and economy, the EU's strategy provides a potentially replicable model that could help Thailand to decarbonize its transport sector and align it with national climate goals.

The Top Runner Program in Japan demonstrates an effective regulatory strategy for enhancing vehicle energy efficiency through the establishment of dynamic performance benchmarks derived from the most energy-efficient models available in the market. This mechanism promotes ongoing technological innovation and has led to notable enhancements in fuel economy within Japan's passenger vehicle fleet. The program's effectiveness is attributed to its adaptability, transparency, and applicability across various industries [70]. Thailand's adoption of a performance-based standard could enhance current fuel economy policies and incentivize manufacturers to achieve above minimum efficiency requirements. The potential for large emission reductions in Thailand from these measures requires evaluation of Thai-specific factors, including vehicle fleet mix, regulatory infrastructure, economic viability, and public acceptance.

One of the important mitigation measures for curbing greenhouse gases (GHGs) and air pollutants is vehicle electrification, especially in the light-duty vehicle (LDV) category. Electric vehicle production is also expected to become more efficient, and electricity production to become cleaner. Studies in several areas have emphasized the emission-reduction

potential of EV penetration. For example, a scenario analysis utilizing the LEAP model regarding Thailand's Government Electric Vehicle Plan (GEV) projects a 21% decrease in CO_2 emissions from passenger transportation by the year 2030, compared to the 2020 baseline [71]. A study by the International Council on Clean Transportation (ICCT) [72] suggests that electrification of 40% of the California light-duty vehicles (LDV) will result in a 50% reduction in nitrogen oxides (NO_x) and a 40% particulate matter (PM) for the state; a 20% reduction in CO_2 emissions in LDV. A report by the European Environment Agency (EEA) found that a 30% take-up of electric vehicles in the EU by 2030 would lead to a 20–25% reduction in emissions of CO_2 in the transport sector. This shift would also result in 25–30% reductions in NO_x and 20–25% reductions in particulate matter [73]. The research by Jenn [74] demonstrates that substantial decreases in greenhouse gas emissions within California's light-duty transportation sector are achievable via vehicle electrification. It is projected that cumulative emissions reductions will reach approximately 1 billion tons of CO_2 by 2045. The implementation of EURO 6 standards for internal combustion engine (ICE) vehicles has proven effective in reducing tailpipe emissions by up to 90% for NO_x and PM compared to older standards. However, the transition to stricter standards, such as EURO 7, faces challenges due to the high costs for automakers and poor enforcement in emerging countries with older vehicle fleets [73]. After 2050, the life-cycle emissions of a typical electric vehicle are projected to decrease by at least 73% per year [66]. Additionally, prior research has demonstrated that the implementation of electric vehicles (EVs) can result in substantial reductions in environmental emissions and fuel consumption [75].

Thailand's transport sector faces many real-world barriers to GHG emission reduction. The availability of public electric vehicle (EV) charging facilities and the need to upgrade the national infrastructure to meet increased electricity consumption are major obstacles. The high cost of electric and low-emission vehicles impedes market penetration, especially for middle- and low-income consumers. The transition is complicated by cultural preferences for private vehicles, a lack of environmental awareness, and low public support for public transit and non-motorized mobility. Delays in stronger emission requirements, inadequate fleet modernization incentives, and the delayed implementation of Euro 5 and Euro 6 fuel quality criteria reduce the efficacy of current programs [76–78]. To transition to low-carbon transport in Thailand, targeted infrastructure investment, fiscal incentives, public education programs, and institutional coordination are needed. Strengthening national data systems and vehicle inspection systems will also be required to adequately monitor and enforce such measures effectively.

This study suggests that electric vehicles may reduce emissions from conventional petroleum-fueled vehicles across all scenarios. However, in the context of increasing transport demand, electric vehicles alone are insufficient for achieving sustainable road transport. CO_2 is emitted directly from the thermal oxidation of fuel, while other gases, NO_x, CO, and PM can be controlled by after-treatment technologies, such as catalytic converters, particulate filters, and selective catalytic reduction systems. The tedious CO_2 enrichment with a conventional emission control device is not sufficiently useful. To effectively control CO_2 emissions, fuel consumption must be reduced, which can be performed by increasing fuel efficiency or replacing these with low-carbon fuels or alternative propulsion technologies [6,79,80].

The electrification of the transport sector, without a corresponding increase in cleaner and renewable technologies within the power sector, could lead to negligible reductions in greenhouse gas emissions or possibly an overall increase in emissions. As highlighted by Rajbhandari et al. [81], the structure of the electricity grid significantly determines the emission outcomes of EV deployment. The potential for reducing GHG emissions through EVs is significantly affected by the carbon intensity of the electricity used for

their charging. In Thailand, the energy sector largely depends on fossil fuels, with about 64% derived from natural gas, alongside a considerable contribution from coal and lignite. This reliance on fossil fuels results in high emission intensity, which limits the net GHG reduction benefits of EV adoption. Although EVs can serve as a feasible approach to decarbonizing the transportation sector, their impact is contingent upon an accompanying shift in the energy sector towards low-carbon alternatives [82]. Thus, it is crucial to implement coordinated policy measures that combine the electrification of transportation with the decarbonization of the power sector to optimize the reduction in emissions. Thailand's roadmap for achieving net-zero emissions aims for a 67% share of renewable energy by 2050, alongside the adoption of carbon capture, utilization, and storage (CCUS) technologies. Improving vehicle efficiency and fuel technologies is essential for minimizing total emissions. Transitioning transport activities to more efficient modes, such as from trucks to rail freight or from private vehicles to public transportation options like buses and trains, can significantly influence overall emissions. The proportion of vehicles utilized for land-based passenger and freight transport has increased, thereby increasing the overall adverse effect of the transport sector on greenhouse gas emissions.

Recent advancements in telematics technology present considerable opportunities for improving transport emission analysis and environmental monitoring. Modern vehicles are increasingly equipped with systems that gather and transmit substantial amounts of real-time data, encompassing engine performance, fuel consumption, travel behavior, and geographic location, to remote databases. This expanding data stream serves as a crucial resource for facilitating precise, dynamic, and location-specific emission evaluations. Savickas et al. [83,84] used telematics in agricultural machinery to determine environmental sustainability. The two-part project created a telematics-based operational efficiency framework and an information technology (IT) tool for comparative environmental analysis utilizing machine-level data. Telematics can monitor fuel usage, workload profiles, and spatial activity patterns, which can be applied to road transport.

3.7. Limitations and Suggestions for Future Research

Although the study used vehicle age data collected by the Department of Land Transport and national databases and field survey data on vehicle kilometers traveled (VKT), several limitations of the study should be recognized. The dataset encompasses the complete registered vehicle fleet in Thailand; however, differences in regional mitigation strategies and inconsistencies in data completeness among various vehicle categories could influence the overall representativeness of the findings. Moreover, the VKT estimates were in part based on questionnaires, which are influenced by response bias and recall. In particular, data for older or less common vehicle types may be limited, and assumptions regarding average usage patterns could introduce uncertainties into the emission estimates. We recommend that for better future emissions inventories, more detailed and frequently updated vehicle activity data are needed. While this research did not use telematics-based inputs, we recognize this as a possible future source of data to enhance vehicle emission estimates, particularly for urban mobility where differences in driving patterns, route path options, and idle times can have a major impact on emissions. Ages to come ought to be spent exploring the connections between telematics and such emission models as IVE to improve the temporal and spatial resolution of on-road emissions. In addition, scenario analysis can be improved by using integrated assessment models to look at policy options along with electrification, fuel quality, and energy decarbonization trajectories.

4. Conclusions

Transport-related emissions in developing nations are rising rapidly, with road transport becoming the primary source of greenhouse gas (GHG) emissions in Thailand, attributed to increasing vehicle ownership and travel demand. This research evaluates the opportunities for GHG reduction in the road transportation sector from 2018 to 2030. Emission factors for different vehicle categories and technologies were obtained through the International Vehicle Emissions (IVE) model. Subsequently, emissions were calculated utilizing country-specific data, in accordance with the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. The results indicated that the total GHG emissions were estimated at 23,914.02 $GgCO_2eq$ in the baseline year 2018. The primary sources of contribution are mainly from pickups (24.38%), trucks (20.96%), passenger cars (19.48%), and buses (16.95%). Under a business-as-usual (BAU) scenario, emissions are projected to increase to 43,801.53 $GgCO_2eq$ by 2030, driven by the increase in the number of vehicles and the distance traveled. By the year 2030, it is anticipated that trucks will become the primary source of emissions, followed by passenger cars, pickups, and buses. The finding that CO_2 remains the primary greenhouse gas released by road transportation aligns with the existing literature. This supports the proposed methodological framework, demonstrating that the model outputs closely resemble established emission trends associated with the Thai vehicle fleet and driving conditions.

The analysis of various scenarios underscores the significant potential for reducing emissions through strategic transitions in vehicle technology within Thailand's transportation sector. Fully adopting electric vehicles (EVs) for new registered motorcycles, passenger vehicles, and pickup trucks, along with gradually phasing out older models, could lead to emission reductions estimated between 18% and 64% across different vehicle categories. In the case of trucks, the deployment of compressed natural gas (CNG) fleets or Euro 5-compliant diesel vehicles, alongside fleet modernization, offers more modest but notable reductions (up to 36.26%). On a broader scale, the implementation of cleaner technologies by EVs at 50% and 100% levels across all vehicle types is anticipated to lower overall GHG emissions by 36.15% and 39.65%, respectively, by the year 2030. The most effective integrated scenario, which includes fully adopting EVs for new motorcycles, passenger cars, and pickups, as well as 50% Euro 5 compliant diesel trucks, could achieve a reduction of up to 41.96% relative to the BAU path. These results highlight the essential importance of rapid fleet electrification and stringent regulatory standards in meeting the country's climate objectives.

While electrification offers a promising low-carbon alternative, its success depends on concurrent efforts to decarbonize the national power grid. Therefore, coordinated policy measures are necessary, including (1) investment in EV charging infrastructure, (2) fiscal incentives to lower the initial cost of EVs, (3) swift implementation of Euro 5/6 emission standards, and (4) public awareness initiatives to encourage sustainable transport choices. Transitioning to renewable energy sources, enhancing energy efficiency, along with exploring alternative propulsion technologies will be equally important for achieving Thailand's net-zero goals. Effective institutional coordination among transport, energy, and environmental agencies will be crucial in ensuring policy coherence and success. The results of this study provide an evidence-based framework to support national transport and climate policy planning. They can assist in developing Thailand's emission inventories, support national climate goals, and create pathways for achieving significant and sustainable GHG reductions in the transportation sector.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/cleantechnol7030060/s1, Table S1: Country-specific, technology-based emission factors classified by vehicle types for the base year 2018.

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