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Analysis of factors affecting energy consumption and CO_2 emissions in Thailand's road passenger transport

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ABSTRACT

The transport sector is one of the important contributors of increasing energy consumption and CO_2 emissions in Thailand. Due to rapid development of transport infrastructure and technologies, patterns of energy consumption in this sector, as well as emissions, have changed considerably. To understand changes of aggregate energy consumption and CO_2 emissions in this sector, this study employs the decomposition technique of the additive LMDI-I index method to analyze influencing factors in the road passenger transport in Thailand during 2007–2017. Results indicate that major energy consumption and GHG emissions in Thailand's road passenger transport come from sedans, vans, and taxis. The decreasing GHG emissions from fuel share and emission factors revealed the success of biofuel promotion in the road transport. The policy implication on energy efficiency and CO_2 mitigation suggests that Thailand should continue promotion of energy efficiency improvement, public transport, biofuels and electric vehicles.

1. Introduction

1.1. Situations of global GHG emissions

The global greenhouse gases emissions increased from 33.82 Gt CO_2eq in 1990 to 48.28 Gt CO_2eq in 2013 (CAIT, 2017), resulting in increasing the average global surface temperature by 0.6 °C (NASA, 2014). In 1988, the Intergovernmental Panel on Climate Change (IPCC) was established by cooperation of the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) (IPCC, 2019). The IPCC published the scientific evidence on global warming effects in its first assessment report (FAR) in 1990. In 1992, the United Nations Framework Convention on Climate Change or UNFCCC was adopted with the aim of stabilization of greenhouse gas (GHG) concentrations in the atmosphere that would prevent dangerous interference with the climate system (UN, 1992). In 1997, the Kyoto Protocol (KP) was adopted at COP3. The KP aimed at reducing GHG emissions (UNFCCC, 2008). At the 18th session of the Conference of the Parties (COP18) in Doha, one of the important outcomes was Nationally Appropriate Mitigation Actions (NAMAs). NAMAs aimed at stimulating the developing countries to reduce their emissions in 2020. The outcome of COP21 is the Paris Agreement, a new international treaty within the UNFCCC, dealing with GHG mitigation, adaptation, and finance. The Paris Agreement aims to limit global surface temperature increases to less than 2 °C when compared to the pre-industrial revolution (Rumjaun et al., 2018; Pita et al., 2017). The Intended Nationally Determined Contributions (INDCs) are a core part of this agreement, which assist the Parties to achieve the long-term target. The Paris Agreement provides the framework of global climate action to all Parties. In order to accomplish the aim of the Paris Agreement, the outcomes from COP24 at Katowice provide the rulebook about how the necessities of the Paris Agreement will be met in key areas.

The achievement of the Paris Agreement is uncertain. The Climate Action Tracker tracks the progress of the mitigation action and evaluates the potential of mitigation commitments. Results have indicated that the emission target limiting the global surface temperature increase to less than 2 °C in 2100 would be unsuccessful under the current policies even with the NDCs. To limit warming to below 2 degrees Celsius, GHG emissions need to be reduced rapidly and brought to zero around mid-century. Additionally, the IPCC Special Report on 1.5 °C suggests the

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strong mitigation actions in promoting renewable energy as well as carbon capture storage.

1.2. GHG emissions and energy consumption in Thailand

In 2016, the world top three GHG emitters were China, the United States and the European Unions (27 countries) (Ge and Friedrich, 2020). In 2016, China contributed 25.76 percent of global GHG emissions. In 2016, Thailand was ranked 18th and contributed only 0.86 percent of global GHG emissions. Thailand, as a member of the non-annex I parties of UNFCCC, has to submit both National Communications (NCs) and Biennial Update Reports (BURs) to the UNFCCC in order to provide information about the situation of the country (UNFCCC, 2020) (UNFCCC, 2019). These reports provide information on GHG inventories, mitigation and adaptation on climate change, and any other information that the parties consider relevant to the achievement of the objective of UNFCCC. Furthermore, regarding the GHG mitigation endeavors of Thailand to support the Kyoto Protocol, Thailand's Nationally Appropriate Mitigation Actions (Thailand's NAMAs) as the voluntary commitment will reduce the GHG emissions by 7–20 percent compared to its business as usual (BAU) levels in the energy and transport sectors in 2020 (UNFCCC, 2014). The base year of Thailand's NAMAs was 2005. Under the BAU, the emissions in the energy and transport sectors in 2020 will be 358.56 Mt CO_2eq. To undertake an ambitious effort with more contributions to combat climate change, Thailand's Nationally Determined Contribution (NDC) intends to reduce economy-wide GHG emissions, excluding LULUCF, by 20 percent and up to 25 percent with adequate support from the BAU emission level in 2030 (Pita et al., 2017; UNFCCC, 2015a; UNFCCC, 2015b).

Thailand's national greenhouse gas inventories can be categorized into five sectors of sources and sinks; 1) energy, 2) industrial processes and product use (IPPU), 3) agriculture, 4) LULUCF, and 5) waste (IPCC, 2018). During 2000–2013, total emissions from energy, IPPU, agriculture, and waste grew by about 2.83 percent of annual average growth rate (AAGR). The energy sector had the largest share. It increased from 71.21 to 74.34 percent in the same period, increasing about 3.02 percent of the AAGR. During 2000–2013, the emissions increased from 156 Mt CO_2eq to 227 Mt CO_2eq, and accounted for 2.94 percent of AAGR (ONEP, 2018). Fuel combustion activities are separated into supply and demand sides. On the supply side, energy industries are included. On the demand side, there are three sub-sectors, including transport, manufacturing industries and construction, and others.

In Thailand, the ratio of emissions in the supply to the demand sides was about 40:60 during 2000–2013, and emissions from the supply side were increased by 34 Mt CO_2eq with 3.26 percent of AAGR. Emissions from the demand side were increased by 37.58 Mt CO_2eq or grew by 2.70 percent of AAGR, whereas the transport sector emitted almost half of the total emissions on the demand side. However, the share of emissions in the transport sector was slightly decreased from 51.96 percent in 2000 to 47.69 percent in 2013 due to an increasing share of biofuels since 2003. Thus, the transport sector plays a major role in national GHG emissions.

The energy consumption has increased continually, especially in the energy sector. Thailand has encouraged renewable energy (RE) utilization since 2000. Figure 1 shows the trend of the emission and energy consumption. During 2000–2005, both trends changed in the same direction with AAGR of 5.46 percent and 5.13 percent, respectively. During 2005–2013, emissions increased with an AAGR of 1.39 percent. However, in the same period the energy consumption increased with an AAGR of 2.17 percent.

From the energy consumption perspective, the share of energy uses on the supply side was higher than the demand side. During 2000–2013, share of energy uses in the energy industries for power generation was almost constant at 60 percent of overall energy used in the country. Their consumption was increased from 60.04 Mtoe in 2000 to 89.16 Mtoe in 2013, and accounted for 3.09 percent of AAGR. The energy consumption of the transport and manufacturing sectors increased by 27 Mtoe in 2013

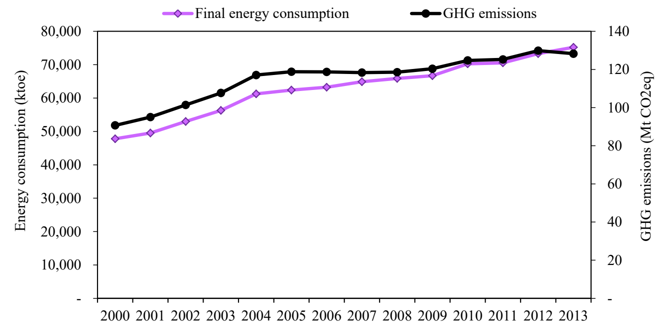


Figure 1. Trends of emissions and energy consumption.

or 3.55 percent of AAGR in the same period. On the demand side, the transport sector was the largest energy consuming sector. Its share was more than 40 percent of total energy consumption in 2013, followed by the manufacturing industries and constructions (around 35 percent), and others.

Generally, the transport mode comprises road, air, water and rail. In many developed countries, such as Japan, Europe, Germany and North America, rail is a favourite mode of transport (IEA, 2019), but in developing countries, road transport plays a major role in transportation resulting in traffic problems and less efficient use of energy. Similarly, the road transport in Thailand has been the major transport mode, which contributed almost 80 percent of energy consumption in the transport sector (DEDE, 2020).

Thus, the transport sector is one of the important contributors of increasing energy consumption and GHG emissions. The objective of this study is to access factors influencing energy consumption and energy-related emissions in Thailand's road passenger transport using the log-mean Divisia index method I (LMDI-I). This study found that population, standard of living, and purchasing power influenced increasing energy consumption and GHG emissions during 2007–2017, but biofuel substitution in the road transport, energy efficiency improvements, and improvement of public transport systems in Thailand resulted in decreasing GHG emissions.

2. Overview of decomposition method and data collection

2.1. Thailand's road transport

The road transport is divided into passenger and freight transports. During 2000 to 2013, the energy consumption in the passenger transport was more than 60 percent of total energy consumption in the road transport. For passenger transport, six vehicle types are considered. They are sedans, vans, motor tricycles (tuk-tuks), taxis, buses and motorcycles. Motorcycles and sedans shared more than 96 percent of total passenger vehicles. They accounted for 58 percent of the energy consumption in passenger vehicles. Electricity has been used in EVs and electric bikes since 2006. The registered number of electric bikes had continually increased between 2006 and 2010, but it has largely decreased after 2010. Owing to decreasing EVs and electric bikes, electricity consumption was reduced by 16.45 percent during 2010–2011.

There are ten types of fuels used in Thailand's road transport. Before 2003, there were only three types of fuels: gasoline, diesel and liquefied petroleum gas (LPG). There are two types of gasoline: gasoline with octane 91 (RON91) and gasoline with octane 95 (RON95). Since 2003, ethanol blended with gasolines by 10%, called gasohol 91 (E10_91) and gasohol 95 (E10_95), were implemented. E20 and E85, ethanol blended with RON95 gasoline by 20% and 85%, were introduced to the market in 2008 and 2010, respectively. Diesel blended with 5% methanol, called biodiesel 5 (B5) was implemented during 2005–2011. Diesel has been replaced by biodiesel completely since 2011 in Thailand. However, the share of blended methanol in biodiesels depends on availability of palm oils in the market. For alternative fuels, LPG has been used in taxis since 1970, and it has been widely used in buses and private vehicles since 2004. The Thai government has promoted and subsidized the use of compressed natural gas (CNG), especially in taxis, buses, trucks, and passenger vehicles, since 2006. In addition, electric vehicles (EVs) have been promoted to improve energy efficiency and reduce GHG emissions from fossil fuel combustion. Another important benefit of EVs is to improve the quality of life in terms of health and the environment, which will lead to sustainable transport development, especially in the urban areas. In 2013, for fuel types, diesel had the largest energy consumption share (53.75%), followed by gasohol (19.59%), CNG (13.71%), LPG (10.50%) and the rest were gasoline and electricity.

2.2. Decomposition general concept and application

Originally, the decomposition method was used for economic analyses, based on the mathematical instrument, which decomposed an aggregate value of prices and corresponding quantity effects. After the world oil crisis in the 1980s, the decomposition method has been applied to many fields of studies; for example, water use, raw materials, goods production, toxic chemical management, and energy and the environment (Ang, 2015). There are many approaches to the decomposition method. Laspeyres and Divisia indices are the two most popular approaches (Ang, 2004). The Laspeyres index is based on the concept of percentage change while the Divisia index is based on the logarithmic theory. Each can be divided into multiplicative and additive techniques with the types of formulae as detailed in Figure 2 (Ang, 2004). The multiplicative decomposition technique is a “ratio” change of an aggregate, but the additive one is a “difference” change of it. The Laspeyres index using the multiplicative decomposition technique consists of conventional and modified Fisher ideal indices (Boyd and Roop, 2004) The additive decomposition technique consists of Shapley/Sun and Marshall-Edgeworth indices (Sun and Ang, 2000). All techniques are perfect decompositions which do not leave residuals However, there are several limitations on the complexity of formulae and difficulty of result interpretation (Mishina and Muromachi, 2012).

Therefore, most studies employ the Divisia index because of its advantages over the above problems. Although the Divisia index approach is divided into two terms of multiplicative and additive, each consists of the log-mean Divisia index method I (LMDI-I) and arithmetic mean Divisia index I (AMDI-I). Based on an arithmetic mean weight function, the AMDI-I formula is more common and easier than the LMDI-I, but there are still some limitations on factor-reversal and zero value tests (Ang, 2004). The factor-reversal test shows the AMDI-I results which give a large residual term in the case that data variations between two sources are large; the residual terms are yearly accumulated over a long period of time; and decomposition on a non-chaining basis and the two decomposition years extend over a wide time span. The zero-value test shows the AMDI-I fails when the data set contains zero values. On the other hand, even though the LMDI-I contains other problems concerning negative and zero value tests, they are proven and resolved. Optional guidelines resolving the negative values are proposed by Ang and Liu (Ang and Liu, 2007b). while the zero values can be resolved by substitution with a small value ($10^{-10}-10^{-20}$) (Ang and Liu, 2007a; Wood and Lenzen, 2006). In addition, selecting the type of LMDI-I index depends on the desirable indicators; the multiplicative index is appropriate for intensity indicators, but the additive one is more suitable for quantity indicators. More suggestions for implementing the LMDI decomposition approaches are presented by (Ang, 2005, 2015). However, this study employs the additive LMDI-I index to specify the amount of each indicator influencing changes in both energy use and related emissions.

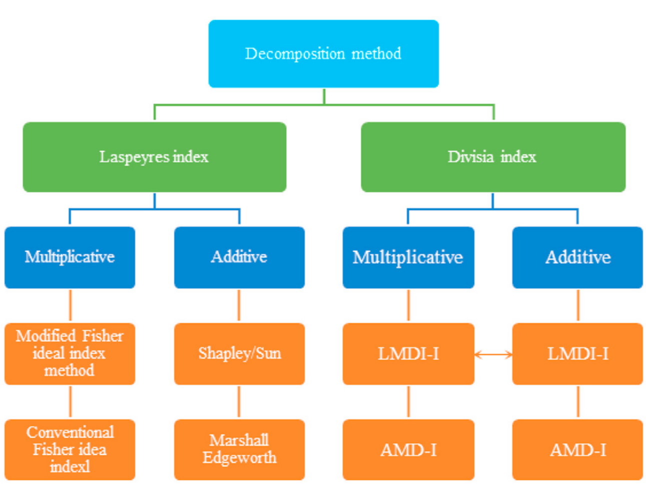


Figure 2. Classification of the decomposition method.

The decomposition method is one of the important methods for policy makers. It is one of the tools for studying the correlation of various factors that influence changes in energy consumption and GHG emissions. Several studies have covered power generation, the manufacturing industry, and the transport, residential and commercial sectors. Normally, socio-economic factors, activity structure and energy intensity have been employed to be input data. Socio-economics refers to the interaction of social and economic factors, i.e. population, GDP, employment, etc. Activity structure refers to any activity that has effects on changes of energy consumption or energy-related environments; for example, the effects of household size or number of people on electricity demand or LPG consumption. The share of industrial sub-sectors influences energy consumption patterns in each country. For instance, fabricated metal industries in Thailand consume mainly electricity, and account for more than 80 percent of overall energy consumption while food and beverages industries consume both electricity (25%) and non-electricity (75%) fuels such as bagasse, agricultural waste and biogas (DEDE, 2013). In the transport sector, the number of vehicles, travel distance and travel behavior affect the fuel consumption pattern. Energy intensity reflects the amount of energy used for an activity, such as LPG consumption in a household, electricity consumption per GDP, gasoline use per vehicle-km or passenger-km. The emission coefficient determines the amount of emissions by a quantity of fuel used, such as emissions of CO_2 from a tonne of coal or N_2O from a quantity of natural gas used.

In the case of Thailand, this method was employed to investigate the effects on changes of both energy and emissions in the power generation, industrial, residential and transportation sectors. In the power sector, factors effecting changes of CO_2 emissions from thermal power plants (Ang and Goh, 2016; Muangthai et al., 2014) and NO_x (Shrestha and Timilsina, 1998) with SO_2 (Ram and Shrestha, 1997) emission intensities from all power plant types were analysed by the decomposition method. For the manufacturing industries, the analyses on changes of energy (Bhattacharyya and Ussanarassamee, 2005; Chontanawat et al., 2014) and CO_2 intensities indicated that growth of socio-economic indicators, GDP together with population, were important influencing factors (Bhattacharyya and Ussanarassamee, 2004; Winyuchakrit and Limmeechokchai, 2016b). In the residential sector, the economic aspects of household consumption in Southeast Asian countries were decomposed and shown to be driven by many factors, especially household income as well as household size (Nguyen, 2018). These socio-economic factors indicated that they are direct factors influencing changes in energy use and emissions (Poolsawat and Wongsapai, 2018).

The traffic activities generally refer to vehicle-km, passenger-km, and tonne-km. This information is available from statistical and annual reports for developed countries, but not for developing countries. Therefore, indirect information which was derived from analyses was used (Winyuchakrit and Limmeechokchai, 2016a). Timilsina (Timilsina and Shrestha, 2009) investigated growth of CO_2 emissions in Asia without intensive analyses on traffic activities. Both past studies focused on the statistics at the national transportation level.

Many past studies focused on the factors affecting changes of energy consumption in the transport sector (see Table 1). These factors were classified in three main groups: socio-economic, traffic activity and fuel economy. Therefore, this study employs the additive LMDI-I index to analyze factors influencing changes of energy consumption and GHG emissions in the road passenger transport in Thailand. In this paper, vehicle types and fuel types are analyzed to understand how changes of vehicle types and fuel substitution affect GHG emissions in Thailand's road passenger transport.

In developed countries, general influencing factors used to analyze energy consumption and GHG emissions in the transportation are separated into 4 groups, as presented in Table 1. The socio-economic (SC) may include population (POP), economic output (EO), and worker income intensity (WI). POP refers to the number of people living in the country. EO is the total value of all goods and services produced in an economy such as GDP, per capita GDP, and share of GDP by economic sector. WI refers to the number of employed people per unit of GDP. The traffic activity (TA) analysis may include use intensity (UI) and mode-share (MS). UI is explained in terms of vehicle use or amount of travel distance, and refers to travel distance per number of vehicles, average distance, vehicles per POP, number of trips, PKM per capita, etc. MS is explained in terms of sharing of transport mode or vehicle type. It refers to share of vehicle-km, share of passenger-km, and share of tonne-km. Fuel economy (FE) refers to the terms of energy intensity (EI) and fuel mix (FM). Finally, emission coefficient (EC) refers to the carbon intensity (CI) of fuel type.

The country's standard of living (CS) and purchasing power (PP) are employed to be the driven factors under the SC group. The CS is explained in terms of the country's economic output. It refers to GDP per capita. The PP is explained in terms of income of vehicle owners. It refers to the number of registered vehicles per GDP. Travel volume demand in terms of passenger-km (PKM) is used as traffic activity because it can reflect the pattern of vehicle use. For FE, the specific energy consumption (SEC) and share of energy consumption (FS) by vehicle and fuel types are used. The SEC, indicating energy efficiency of vehicle, refers to the amount of energy consumption per PKM. The FS indicates the pattern of fuel substitution for the analysis of energy-related emissions and refers to consumption share of different fuels. A summary of influencing factors considered in this study is presented in Table 2.

Regarding the influencing factors described above, equations used to analyze changes of energy consumption and GHG emissions in Thailand's road passenger transport in year t can be written in (1(1) and (2)(2). In this study, vehicles are categorized into six types, including sedan, van, tuk-tuk, taxi, bus and motorcycle. Ten fuel types, including LPG, RON95, RON91, diesel, CNG, E10_95, E10_91, E20, E85 and electricity are considered.

$$EC^t = \sum_i EC_i^t = \sum_i (POP^t) \times \left(\frac{GDP^t}{POP^t}\right) \times \left(\frac{NV_i^t}{GDP^t}\right) \times \left(\frac{PKM_i^t}{NV_i^t}\right) \times \left(\frac{EC_i^t}{PKM_i^t}\right) \quad (1)$$

$$GHG^t = \sum_{i,j} GHG_{i,j}^t = \sum_{i,j} EC_i^t \times \left(\frac{EC_{i,j}^t}{EC_i^t}\right) \times \left(\frac{GHG_{i,j}^t}{EC_{i,j}^t}\right) \quad (2)$$

where

EC^t: total energy consumption in year t (PJ)

POP^t: population in year t (million people)

GDP^t: gross domestic product in year t (trillion Baht)

NV_i^t: number of registered vehicles type i in year t (million vehicles)

PKM_i^t: passenger kilometers of vehicle type i in year t (passenger-billion kilometers)

EC_i^t: energy consumption of vehicle type i in year t (PJ)

$EC_{i,j}^t$: energy consumption of vehicle type i and fuel type j in year t (PJ)

GHG^t: total GHG emissions in year t (Mt CO_2eq)

$\frac{GHG_{i,j}^t}{EC_{i,j}^t}$: GHG emissions of vehicle type i and fuel type j in year t per energy consumption of vehicle type i and fuel type j in year t (Mt CO_2eq/PJ)

Eqs. (1) and (2) can be rewritten as (3) and (4), respectively.

Table 1. Summary of influencing factors used to analyze energy consumption and GHG emissions in the transport sector.

Author	Analysis area	year	Driving factor							
			SC			TA		FE		EC
			POP	EO	WI	UI	MS	EI	FM	CI
S. Solaymani	Global	2019	√	√				√	√	√
Rocío Román-Collado and Any Viviana Morales-Carrión	Latin America	2018	√	√				√		√
R. Roman-Collado et al.	Colombia	2018	√	√				√		
Vehmas, J., Kaivo-oja, J., & Luukkanen, J.	EU-28	2018	√	√				√		
O.Y. Edelenbosch et al.	Global	2017	√			√	√	√		√
Y. Mishina and Y. Muromachi	Japan	2017					√	√		√
A. Roinioti and C. Koroneos	Greece	2017		√				√		√
F. Fan and Y. Lei	China	2016	√	√		√		√	√	√
H. Achour and M. Belloumi	Tunisia	2016	√	√		√	√	√		
Y. Dai and H.O. Gao	China	2016		√		√	√	√		
L Andres and E. Padilla	Spain	2015					√	√		
J. Jiang	Japan	2015	√			√	√	√		
N. Sobrino and A. Monzon	Spain	2014		√	√	√	√	√		√
X. Xu et al.	China	2014		√				√	√	√
Hui-Min Wu and Wu Xu	China	2014		√		√	√	√		
T. O′ Mahhony et al.	Ireland	2013				√	√	√	√	√
Y. Mishina and Y. Muromachi	Japan	2012	√			√	√	√		√
Y. Mishina et al.	Japan	2011	√			√	√	√		
W.W. Wang et al.	China	2011	√	√		√	√		√	√
M. Zhang et al.	China	2011				√	√	√		
K. Papagiannaki and D. Diakokulaki	Greece and Denmark	2009	√			√	√	√	√	

Table 2. Description of factors influencing on changes of energy use and energy-related emissions.

Group	Influencing factor	Input	Description
SC	POP	POP	POP is population. Population effect on change of energy demand, resulting in changing level of both energy consumption and emissions.
	CS	$\frac{GDP}{POP}$	The country's standard of living explains the correlation between personal income and change of energy consumption and GHG emissions.
	PP	$\frac{NV}{GDP}$	Purchasing power interprets the pattern of new vehicles on economic growth.
TA	TD	$\frac{PKM}{NV}$	Travel volume demand reflects the pattern of vehicle use on the people. The increase of travel volume demand increases annual travel distance.
FE	SEC	$\frac{EC}{PKM}$	Specific energy consumption reflects the quality of energy use by vehicle types. Decreasing SEC means that the vehicle improves the energy efficiency
	FS	$\frac{EC}{EC_t}$	Fuel share reflects the pattern of fuel substitution.
EC	EF	$\frac{GHG}{EC}$	Emission factor reflects the quality of using clean energy. The decrease means greater use of clean energy

$$EC^t = \sum_i (POP^t \times CS^t \times PP_i^t \times TD_i^t \times SEC_i^t) \quad (3)$$

$$GHG^t = \sum_{i,j} \left(POP^t \times CS^t \times PP_i^t \times TD_i^t \times SEC_i^t \times FS_{ij}^t \times EF_{ij}^t\right) \quad (4)$$

where

POP^t: Thailand population in year t (million people)

CS^t: country's standard of living in year t (trillion Baht/million people)

PP_i^t: purchasing power of vehicles type i in year t (million vehicles/trillion Baht)

TD_i^t: travel volume demand of vehicle type i in year t (passenger-billion kilometers/million vehicles)

SEC_i^t: specific energy consumption of vehicle type i in year t (PJ/passenger-billion kilometers)

$FS_{i,j}^t$: share of energy consumption of vehicle type i and fuel type j in year t

$EF_{i,j}^t$: GHG emissions factor of vehicle type i and fuel type j in year t (Mt CO_2eq/PJ)

In additive LMDI-I decomposition, the changes of energy consumption (ΔEC) and GHG emissions (ΔGHG) from the road passenger transport between year t and year 0 are calculated as (5) and (6), respectively.

$$\begin{aligned}\Delta EC &= EC^t - EC^0\\ &= \sum_i (POP^t \times CS^t \times PP_i^t \times TD_i^t \times SEC_i^t) - \sum_i (POP^0 \times CS^0 \times PP_i^0 \times TD_i^0 \times SEC_i^0)\\ &= \Delta POP + \Delta CS + \Delta P + \Delta TD + \Delta SEC + \Delta FS \end{aligned} \quad (5)$$

$$\begin{aligned}\Delta GHG &= GHG^t - GHG^0\\ &= \sum_{i,j}\left(POP^t \times CS^t \times PP_i^t \times TD_i^t \times SEC_i^t \times FS_{ij}^t \times EF_{ij}^t\right)\\ &- \sum_{i,j}\left(POP^0 \times CS^0 \times PP_i^0 \times TD_i^0 \times SEC_i^0 \times FS_{ij}^0 \times EF_{ij}^0\right)\\ &= \Delta POP + \Delta CS + \Delta PP + \Delta TD + \Delta SEC + \Delta FS + \Delta EF \end{aligned} \quad (6)$$

For changing of energy consumption, the formulae for the effects of each factor by the additive LMDI-I decomposition are given as Eqs. (7), (8), (9), (10), and (11).

$$\Delta POP = \sum_i \left(\frac{EC_i^t - EC_i^0}{\ln EC_i^t - \ln EC_i^0}\right) \ln\left(\frac{POP^t}{POP^0}\right) \quad (7)$$

$$\Delta CS = \sum_i \left(\frac{EC_i^t - EC_i^0}{\ln EC_i^t - \ln EC_i^0}\right) \ln\left(\frac{CS^t}{CS^0}\right) \quad (8)$$

$$\Delta PP = \sum_i \left(\frac{EC_i^t - EC_i^0}{\ln EC_i^t - \ln EC_i^0}\right) \ln\left(\frac{PP^t}{PP^0}\right) \quad (9)$$

$$\Delta TD = \sum_i \left(\frac{EC_i^t - EC_i^0}{\ln EC_i^t - \ln EC_i^0}\right) \ln\left(\frac{TD^t}{TD^0}\right) \quad (10)$$

$$\Delta SEC = \sum_i \left(\frac{EC_i^t - EC_i^0}{\ln EC_i^t - \ln EC_i^0}\right) \ln\left(\frac{SEC^t}{SEC^0}\right) \quad (11)$$

For changing of GHG emissions, the formulae for the effects of each factor by the additive LMDI-I decomposition are given as Eqs. (12), (13), (14), (15), (16), (17), and (18).

$$\Delta POP = \sum_{i,j} \left(\frac{EC_{ij}^t - EC_{ij}^0}{\ln EC_{ij}^t - \ln EC_{ij}^0}\right) \ln\left(\frac{POP^t}{POP^0}\right) \quad (12)$$

$$\Delta CS = \sum_{i,j} \left(\frac{EC_{ij}^t - EC_{ij}^0}{\ln EC_{ij}^t - \ln EC_{ij}^0}\right) \ln\left(\frac{CS^t}{CS^0}\right) \quad (13)$$

$$\Delta PP = \sum_{i,j} \left(\frac{EC_{ij}^t - EC_{ij}^0}{\ln EC_{ij}^t - \ln EC_{ij}^0}\right) \ln\left(\frac{PP^t}{PP^0}\right) \quad (14)$$

$$\Delta TD = \sum_{i,j} \left(\frac{EC_{ij}^t - EC_{ij}^0}{\ln EC_{ij}^t - \ln EC_{ij}^0}\right) \ln\left(\frac{TD^t}{TD^0}\right) \quad (15)$$

$$\Delta SEC = \sum_{i,j} \left(\frac{EC_{ij}^t - EC_{ij}^0}{\ln EC_{ij}^t - \ln EC_{ij}^0}\right) \ln\left(\frac{SEC^t}{SEC^0}\right) \quad (16)$$

$$\Delta FS = \sum_{i,j} \left(\frac{EC_{ij}^t - EC_{ij}^0}{\ln EC_{ij}^t - \ln EC_{ij}^0}\right) \ln\left(\frac{FS^t}{FS^0}\right) \quad (17)$$

$$\Delta EF = \sum_{i,j} \left(\frac{EC_{ij}^t - EC_{ij}^0}{\ln EC_{ij}^t - \ln EC_{ij}^0}\right) \ln\left(\frac{EF^t}{EF^0}\right) \quad (18)$$

2.3. Input information

In Thailand, the socio-economic information for more than two decades has been annually published by the governmental agencies, but the other information is limited. Therefore, in order to accomplish the analyses, more information must be collected and investigated appropriately as concluded in Table 3.

Table 3. Summary of input information.

Group	Information	Period of available data	Source
SC	POP	1993–2017	DOPA (2020)
	GDP	1971–2017	NESDC (2020)
T	Number registered vehicles by vehicle type	1989–2017	DLT (2018)
	Passenger-kilometer by vehicle type	2007–2017	DOH (2020)
FE	Energy consumption by transportation mode Energy consumption by vehicle type Energy consumption by vehicle and fuel types	2005–2017 No statistical information No statistical information	DEDE (2020)
EC	GHG emissions	2000–2017	IPCC (2006)

* Note: Period of available data is based on online publication.

2.3.1. Socio-economic information

This information includes population and GDP. Since 1990, population information has been published by the Department of Provincial Administration (DOPA, 2020). Annual information of GDP has been collected from the office of the National Economic and Social Development Council (NESDC, 2020).

2.3.2. Traffic activities

The information of number of registered vehicles and travel volume demand in terms of passenger-kilometers by types of vehicle is required. Number of vehicles by types can be collected from the Department of Land Transport, Ministry of Transport (MOT). Travel volume demands by vehicle types are collected from the Bureau of Highway Safety, Department of Highways (2020) (DOH).

2.3.3. Fuel economy

Fuel economy reflects efficiency of energy consumption. This factor determines the energy consumption per travelling demand; for example, liter/km, GJ/vehicle-km, GJ/passenger-km, etc. In this study, due to the limitation of data, fuel economy in terms of megajoules per thousand passenger-kilometers is used. Information of travel volume demand has been published, but it was uncollected before 2007, while annual total energy consumption has been published and categorized by transportation mode since 1990. The energy consumption information has been published by Ministry of Energy (MOE). Nevertheless, the energy information classified by vehicle and fuel types are absent. Published information of vehicle kilometers travel demand categorized by vehicle type is employed to be a fraction coefficient, identifying the energy consumption categorized by vehicle and fuel types using Eqs. (19) and (20). The methodology used to investigate the energy consumption of road passenger transport in vehicle types and fuel types is presented in Figure 3.

$$EC_{Pass,i,j} = EC_{Road,j} \cdot \%VKT_{Pass,i,j} \tag{19}$$

where:

$EC_{Pass,\ i,j}$: energy consumption of road passenger transport by vehicle type i and fuel type j (PJ)

$EC_{Road,\ j}$: energy consumption of road transport by fuel type j (PJ)

$\%VKT_{Pass,\ i,\ j}$: share of vehicle-kilometer of road passenger transport by vehicle type i and fuel type j (fraction)

$$\%VKT_{Pass,i,j} = VKT_{Pass,i} \cdot share\ of \sum_{i,j} \left(NV_{Pass,i,j} \cdot FE_{Pass,i,j}\right) \tag{20}$$

where $\%VKT_{Pass,\ i,\ j}$: share of vehicle-kilometer of road passenger transport by vehicle type i and fuel type j (fraction)

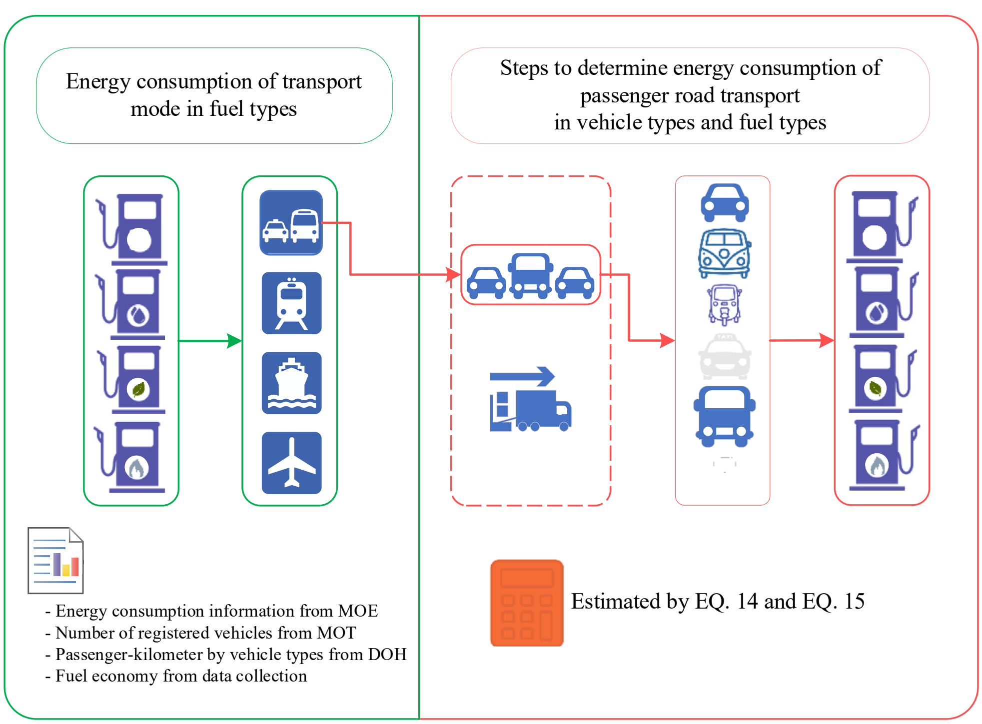


Figure 3. Steps to determine energy consumption in road passenger transport by vehicle and fuel types.

$VKT_{Pass,\ i}$: vehicle-kilometer of road passenger transport by vehicle type i (%)

$NV_{Pass,i,j}$: number registered of road passenger transport by vehicle type i and fuel type j (vehicles)

$FE_{Pass,\ i,\ j}$: fuel economy by vehicle i and fuel type j (PJ)

2.3.4. Emission factor

Emission factor refers to the amount of GHG emissions per unit of energy consumed. In this study, three main GHGs (CO_2, CH_4 and N_2O) are considered from fuel combustion, but renewable energy considers only CH_4 and N_2O (IPCC, 2006). The Global Warming Potential (GWP) adopted from the IPCC Fifth Assessment Report (AR5) (IPCC, 2015) is applied. Without country-specific emission factor information, the default emission factors of all fossil fuels and renewable energies were employed from the 2006 IPCC guidelines. For more delicate consideration in power generation, even default emission factors of fossil fuel were applied, and the calculated emission factor of electricity was varied annually depending on fuel used for electricity generation. Emission factors of bio-oils were calculated and varied annually based on proportion of blended fuels. The proportion of bio-oil in diesel depends on availability of domestic bio-oil supply, which is announced by the Ministry of Energy in the Royal Gazette.

3. Results and discussion

In this section, four points of view are explained and discussed. Firstly, a radical perspective of Thailand's energy consumption and GHG emissions during the period of 2007–2017 is briefly explained to understand the country's situation. Then, changes in energy consumption and GHG emissions by types of vehicle are presented. Next, effects of factors influencing changes of energy consumption and emissions analyzed by the LMDI-I technique are identified. Results are presented in terms of changes in passenger vehicle types. Finally, factors influencing the determination of passenger transport from the policy are summarized, and the policy implications are discussed.

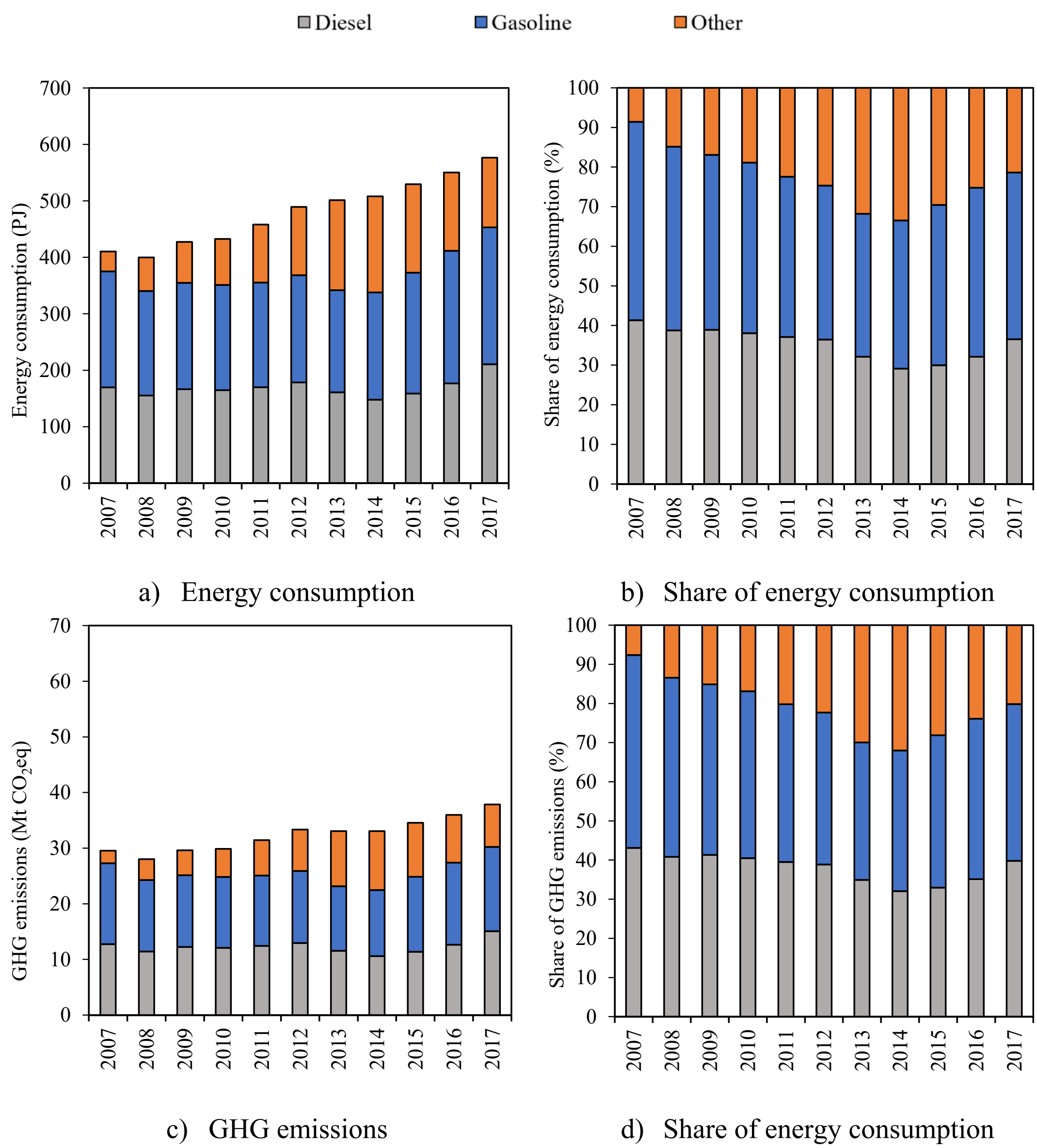


Figure 4. Energy consumption and GHG emissions in the road passenger transportation.

3.1. Radical perspectives of energy consumption and emissions in Thailand's road passenger transport

During the studied period, energy consumption in the road passenger transport in Thailand increased by 166.21 PJ, and accounted for 3.46 percent of AAGR. Fuels used in the road passenger transport can be grouped into three types: diesel, gasoline, and other fuels (shown in Figure 4 a).

The diesel group contains both diesel and biodiesel. Fossil-based diesel has been fully replace by biodiesel since 2007. Diesel is a major fuel used in the freight transport in Thailand. Between 2007 and 2017, diesel consumption increased by 41.06 PJ, and accounted for 2.19 percent of AAGR. However, during the study period, the share of diesel consumption was almost constant at 35 percent of total energy consumption in the road passenger transport.

The gasoline group includes pure gasoline and gasohol. Gasoline consumption increased by 37.01 PJ when compared to 2007, and accounted for 1.67 percent of AAGR. Though the growth rate of gasoline consumption was minor, its consumption was the highest contribution because more than 80 percent of gasoline engines are in the major passenger vehicles in Thailand. The average share of gasoline during 2007–2017 was at 41.97 percent of total energy consumption in the road passenger transport (see Figure 4 b).

Other fuels include LPG, CNG and electricity, but consumption of electricity was insignificant. Due to subsidies on LPG and CNG prices in the passenger vehicles, especially sedans and taxis, their consumption increased significantly by 13.37 percent per year. The amount of both LPG and CNG consumption increased 88.14 PJ during 2007–2017. However, the share consumption was about 22.54 percent of total energy consumption in the road passenger transport.

In the context of energy-related emissions, CO_2 emissions accounted for about 98 percent of overall GHG emissions released from fuel combustion processes of passenger vehicles. Other GHG gases, including CH_4 and N_2O, are insignificant, although the share of CH_4 is high in the other GHG gases. During 2000–2017, GHG emissions increased by 8.33 Mt CO_2eq (see Figure 4 c). The share of GHG emissions from gasoline during 2007–2017 was the highest share, and accounted for 41.03 percent of total GHG emissions in the road passenger transport (see Figure 4 d).

Usually, increases in emissions follow the same trend as energy consumption. However, due to the Alternative Energy Development Plan (AEDP) during 2007–2017, GHG emissions increased by 2.51 percent of AAGR while the energy consumption increased by 3.46 percent of AAGR.

For biofuels, CO_2 emissions are completely removed. Thus, only CH_4 and N_2O are noticeably emitted from biofuel combustion. In 2017, CH_4 and N_2O emissions from biooils had been increased by 0.25 Mt CO_2eq when compared to 2007, and accounted for 38.97 percent of AAGR, while these emissions from conventional fuels had been increased by 8.09 Mt CO_2eq, and accounted for 2.45 percent of AAGR.

Table 4 presents results of GHG emissions and reduction in the road passenger transport. GHG emissions reduction can be estimated from the difference between GHG emissions with and without alternative fuels. All alternative fuels can mitigate accumulative GHG emissions of 18.18 Mt CO_2eq during 2007–2017. Gasohol played an important role with a large share of 73 percent.

3.1.1. Changes of energy consumption and emissions by vehicle types

The increase of energy consumption by 166.21 PJ during 2007–2017 was mainly due to economic development (see Figure 5a), as well as transport policy in the country. Only in 2008 was energy consumption decreased by 10.53 PJ due to an economic slowdown, along with political problems. In 2009, the situations had been resolved. Sedans and taxis were the major energy consumers, resulting in increasing energy consumption by 6.88 percent, when compared to 2008. The energy consumption in sedans, vans and taxis rapidly increased during 2010–2013, but it decreased in motorcycles, resulting in increasing aggregated energy consumption in the transport sector by 15.85 percent. During 2011–2012, the government launched the first car policy to stimulate the economy. However, this policy led to decreasing the use of public transport. Moreover, due to many severe accidents that happened with public vans, traffic safety has been strictly enforced resulting in decreasing the number of public vans. Therefore, energy consumption largely increased in sedans and vans while it decreased in motorcycles. In Thailand, vans normally have been used as public transport and rented vehicles. However, since 2013, when Taxi Grab launched business in Thailand, the share of energy consumption in taxis increased while vans decreased. Since 2014, sedans have played an important role in increasing aggregated energy consumption due to low oil prices in the market.

In terms of emissions, the GHG emissions change during 2007–2017 followed the trend of energy consumption in the road passenger transport (see Figure 5b). In 2017, the energy consumption in the road passenger transport increased by 166.21 PJ when compared to 2007, and accounted for 3.59 percent of AAGR, while GHG emissions increased by 8.33 Mt CO_2eq, and accounted for 2.45 percent of AAGR. Sedans and taxis played a major role in increasing GHG emissions. On the other hand, the trend of GHG emissions from motorcycles decreased during 2011–2014 due to decreasing motorcycles. Results indicated that the change of GHG emissions was not related to energy consumption, but it was related to the types of fuels, especially alternative fuels. For example, during 2012–2014 the growth of energy consumption increased around 3.84 percent of AAGR while the growth of GHG emissions decreased by 0.84 percent of AAGR due to increasing bio-oil consumption.

In terms of the relationship between fuel consumption and number of vehicles, diesel consumption was close to gasoline consumption, but the number of diesel vehicles was smaller than gasoline vehicles. The share of motorcycles was about 84 percent in gasoline vehicles. The number of LPG and CNG vehicles in 2017 declined around 6.12 and 3.78 percent of AAGR, respectively, when compared to 2007. Hybrid vehicles included hybrid gasoline and hybrid diesel vehicles, and accounted for a share of 0.34 percent of total vehicles in 2017 (DLT, 2020). For the decomposition analysis in this paper, hybrid gasoline and hybrid diesel vehicles were grouped in gasoline and diesel vehicles, respectively.

Table 4. The results of GHG emissions and reduction in the road passenger transport.

Mitigation	GHG emissions and reduction (Gg CO_2eq)										
	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Without AF	29,835	28,785	30,599	30,869	32,506	34,578	35,060	35,415	37,103	38,834	40,983
With AF	29,538	28,027	29,614	29,861	31,451	33,344	33,058	33,065	34,567	35,991	37,867
Gasohol	*272*	*530*	*703*	*703*	*698*	*775*	*1,450*	*1,819*	*1,993*	*2,188*	*2,342*
Biodiesel	*25*	*229*	*282*	*305*	*358*	*458*	*551*	*531*	*543*	*656*	*774*
Total	296	759	985	1,008	1,056	1,233	2,002	2,350	2,536	2,843	3,116

* Note: AF is alternative fuel.

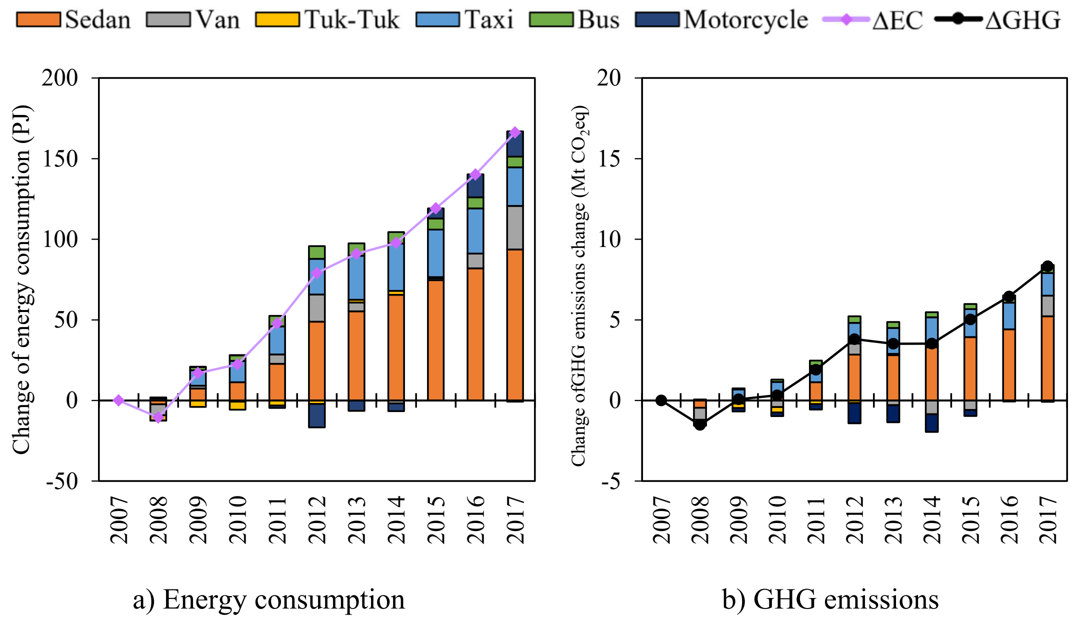


Figure 5. Changes of aggregate energy consumption and GHG emissions by vehicle types.

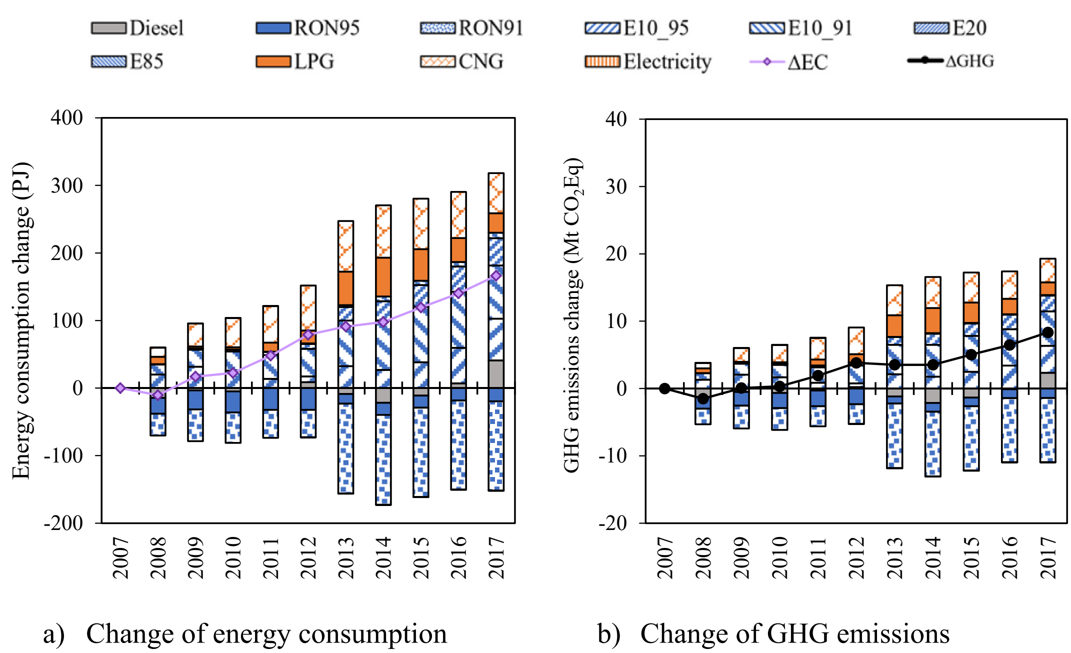


Figure 6. Energy consumption and GHG emissions by fuel types during 2007–2017.

3.1.2. Changes of energy consumption and emissions from fuel substitution

Fuel prices played an important role in terms of changes in energy and emissions. The changes of energy and emissions were divided into two periods: 2007–2014 and 2015–2017.

Diesel consumption decreased by 21.71 PJ in 2014 when compared to 2007. Due to fuel substitution in gasoline vehicles, gasoline consumption in 2017 decreased by 151.08 PJ when compared to 2007, while in the same period gasohol consumption increased by 135.58 PJ (see Figure 6). As a result of increasing world oil prices during 2007–2014, the average diesel retail price in Thailand increased from 0.82[1,2] USD/liter in 2005 to 0.94[1,2] USD/liter in 2014, while average gasoline retail price increased from 0.93[1,2] USD/liter to 1.44[1,2] USD/liter. Therefore, diesel and gasoline were partially substituted by biofuels. According to the AEDP plan, the government has promoted E10 gasohol since 2003. Then, RON91 gasoline was fully phased out in 2012. The share of E10 gasohol in 2007 was about 18.46 percent and increased to 72.64 percent in 2014. The E20 and E85 gasohols were implemented in 2008 and 2010, respectively. In 2014, the share of E20 gasohol was about 15.03 percent and the share of E85 gasohol was about 3.64 percent of total gasoline consumption.

Since 1970, LPG has been promoted to use in tuk-tuks and taxis due to its low price. CNG has been promoted to use in the public vehicles since 1984. Also, CNG has been used to substitute LPG since 2008 because LPG can be upgraded to more valuable petroleum products. During 2007 to 2011, LPG and CNG prices were fixed at 0.69[1,2] USD/liter and 0.27[1,2]

[1] Average exchange rate is 31.22 Baht/US dollar in 2019 (BOT, 2019).
[2] Retail oil prices from PTT (OR, 2020).

USD/kg. The LPG and CNG prices in 2014 increased to 0.97[1,2] USD/liter and 0.36[1,2] USD/kg, respectively. Thus, CNG consumption was higher than LPG consumption. However, due to the small number of CNG stations, as well as long filling time, promotion of CNG was not successful. In Thailand, LPG and CNG prices are lower than diesel and gasoline prices due to subsidy. Thus, consumption of LPG and CNG increased continually during 2007–2014.

In 2017, the retail price of E20 was lower than the RON95 gasoline price by 0.31 USD/liter and lower than the LPG price by 0.18 USD/liter, while the retail price of E85 was lower than the RON95 gasoline price by 0.46 USD/liter and lower than the LPG price by 0.33 USD/liter. Retail prices of LPG and CNG increased to 0.97[1,2] USD/liter and 0.42[1,2] USD/kg, respectively, in 2017.

3.2. LMDI analysis in the road passenger transport by vehicle types

This section presents energy consumption and emissions by vehicle types by using the LMDI-I method in the road passenger transport. There are five factors: population, country's standard of living, purchasing power, travel volume demand and specific energy consumption

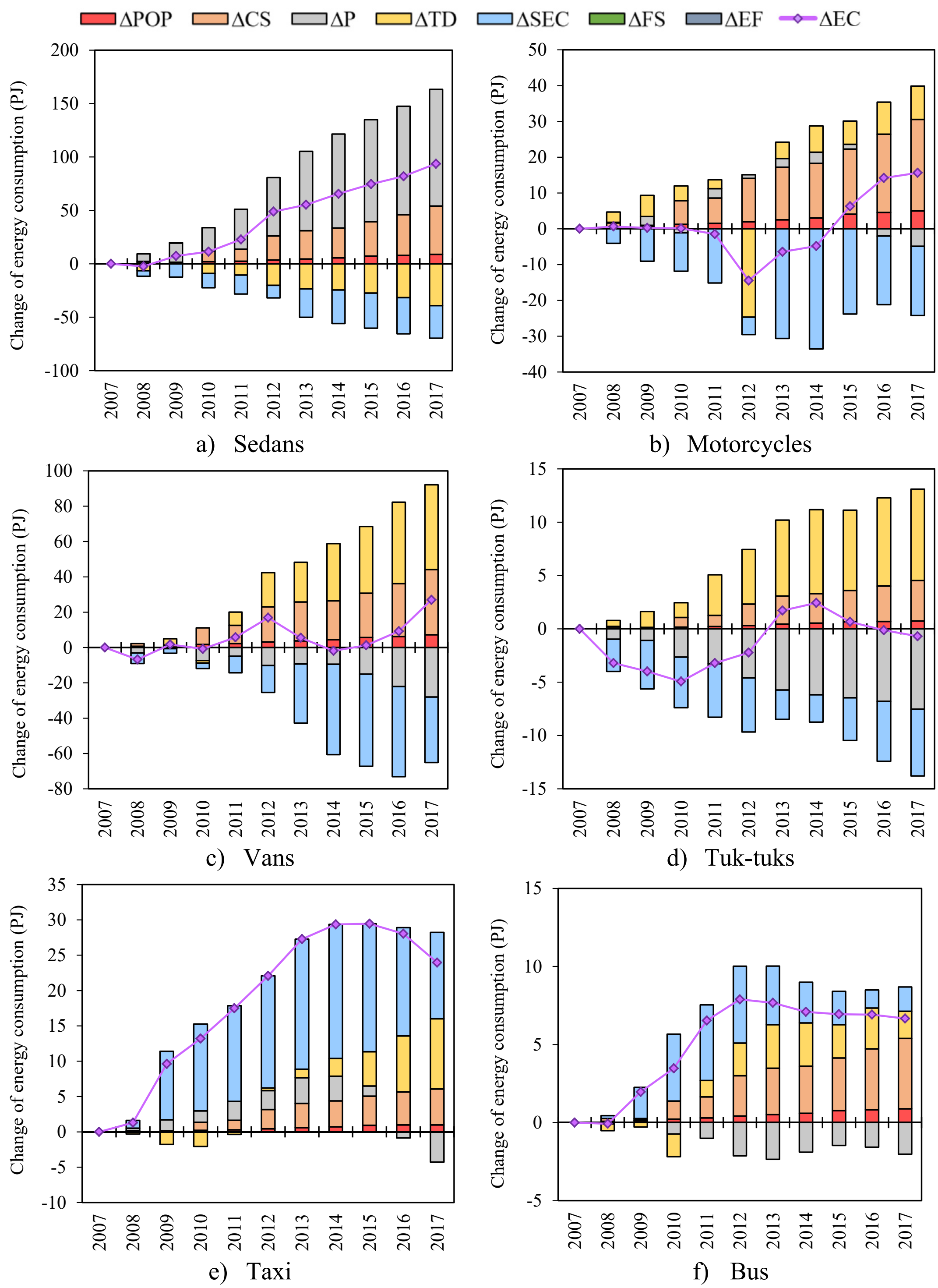


Figure 7. Decomposition results in energy consumption by vehicle types.

influencing changes in energy consumption, and an additional two factors: fuel share and emissions factors influencing changes in emissions.

3.2.1. Sedan

In 2017, energy consumption in sedans increased by 93.66 PJ when compared to 2007 (see Figure 7a). Population, country's standard of living and purchasing power increased energy consumption in sedans, while travel volume demand and specific energy consumption decreased energy consumption. Increasing the country's standard of living results in increased purchasing power. Increasing the country's standard of living and increasing purchasing power resulted in increasing energy consumption in sedans. It increased by 154.46 PJ in 2017 when compared to 2007. Though vehicle ownership increased, travel volume demand decreased resulting in decreasing energy consumption in sedans by 39.16 PJ in 2017 when compared to 2007. Moreover, specific energy consumption of sedans was improved due to energy efficiency improvement and promotion of alternative fuels such as biodiesel and gasohol. Thus, energy consumption in sedans decreased by 30.51 PJ in 2017.

In the beginning of the study period, energy consumption in sedans sharply increased during 2010–2012 due to the first car policy resulting in increasing aggregated energy consumption in the road passenger transport by 4 times. It was also influenced by purchasing power increasing in 2012 by 2.5 times when compared to 2010.

During 2007–2017, GHG emissions increased by 4.32 percent of AAGR while the aggregate energy consumption increased by 5.29 percent of AAGR (See Figure 8a). GHG emissions increased by 5.22 Mt CO_2eq due to the increases of population, country's standard of living and purchasing power factors and decreases in travel volume demand,

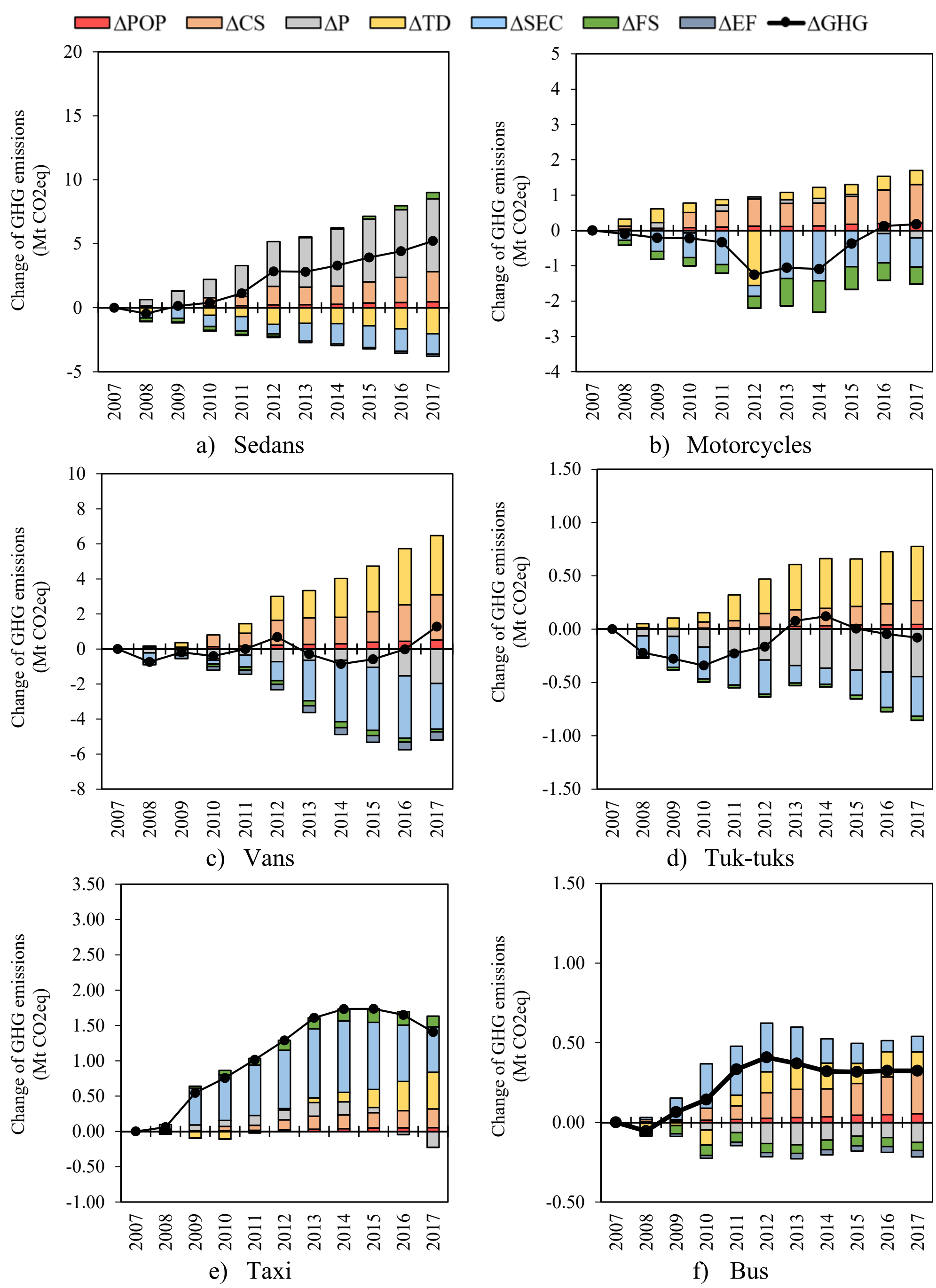


Figure 8. Decomposition results in GHG emissions by vehicle types.

specific energy consumption and emissions factors. Country's standard of living and purchasing power influenced increasing GHG emissions by 8.04 Mt CO_2eq in 2017 when compared to 2007. On the other hand, travel volume demand and specific energy consumption played a major role in decreasing GHG emissions by 3.63 Mt CO_2eq in 2017 when compared to 2007. The fuel share increased GHG emissions by 0.50 Mt CO_2eq in 2017 when compared to 2007. During 2007–2017, increasing gasohol consumption influenced decreasing gasoline consumption. The emission factors decreased GHG emissions due to substitution of alternative fuels for gasoline and diesel.

3.2.2. Motorcycle

During 2007–2017, energy consumption in motorcycles increased by 15.63 PJ due to increasing population, country's standard of living, purchasing power and travel volume demand and decreasing specific energy consumption (see Figure 7b). The country's standard of living and travel volume demand were the dominant factors affecting increasing energy consumption by 34.86 PJ in 2017, while improvement of specific energy consumption significantly decreased energy consumption by 19.34 PJ in the same period.

In 2012, travel volume demand of motorcycles sharply declined as a result of huge floods in the central region of Thailand. Moreover, reduction of travel volume demand directly affected changes to energy efficiency resulting in increasing specific energy consumption by 32.12 percent in 2012 when compared to 2011.

GHG emissions increased by 0.18 Mt CO_2eq in the same period (see Figure 8b). However, growth of GHG emissions was lower than energy consumption. Fuel share played an important role in decreasing GHG emissions by 0.49 Mt CO_2eq in 2017 when compared to 2007. Substitution of E10 gasohol for gasoline was the important driver. The share of gasohol in gasoline consumption was 18.46 percent in 2007 and 92.63 percent in 2017.

3.2.3. Van

In 2017, energy consumption in vans increased by 26.99 PJ when compared to 2007 (see Figure 7c). The country's standard of living and travel volume demand significantly affected increasing energy consumption by 84.88 PJ in 2017, while purchasing power and specific energy consumption affected decreasing energy consumption by 84.88 PJ in the same period. Similarly, in most Southeast Asian countries, especially in Thailand, Cambodia, Laos and Myanmar, vans usually are used for public transport. The change in country's standard of living affect on the decreasing purchasing power. The country's standard of living or GDP per capita resulted in increasing energy consumption by 36.85 PJ in 2017 while purchasing power resulted in decreasing energy consumption by 28.03 PJ in 2017 when compared to 2007. Owing to enforcement of safety laws for vans, uncertified public vans were retired. Therefore, people felt confident in using vans for public transport. The travel volume demand increased and resulted in improvement of energy efficiency. Overall energy consumption increased by 48.03 PJ in 2017, while the specific energy consumption decreased by 37.08 PJ in the same period.

In the context of energy-related emissions, GHG emissions increased by 1.28 Mt CO_2eq in 2017 when compared to 2007 (see Figure 8c). The trend of GHG emissions was the same as energy consumption. The fuel share and emission factors influenced decreasing GHG emissions due to national transport policies. Both fuel share and emission factors decreased GHG emissions by 0.62 Mt CO_2eq in 2017 when compared to 2007.

3.2.4. Tuk-tuk

Tuk-tuks have been used as Thai style taxis in local areas. The share of tuk-tuks in energy consumption was only 3.50 percent of total energy consumption in the road passenger transport. The change of energy consumption in tuk-tuks depended on tourism (see Figure 7d). Energy consumption in tuk-tuks decreased by 0.69 PJ in 2017 when compared to 2007 due to improvement of public transport.

The travel volume demand and the country's standard of living were major factors in increasing energy consumption by 12.36 PJ in 2017 while the purchasing power and specific energy consumption influenced decreasing energy consumption by 13.79 PJ in 2017 when compared to 2007. An increased number of tourists resulted in increasing travel volume demand, as well as per capita GDP. For these reasons, energy consumption increased more than twofold in 2011 and fivefold in 2013.

Electric trains have served as mass transit in Bangkok city since 1999. The trains' service area overlaps the tuk-tuks' service area, which affected the demand for tuk-tuks and tuk-tuk drivers' income. Moreover, the safety regulation for tuk-tuks has been enforced by the Department of Land Transport and, as a result, uncertified tuk-tuks have been retired.

Thus, the decreased purchasing power of tuk-tuks resulted in decreasing energy consumption by 7.53 PJ in 2017. In addition, the specific energy consumption decreased energy consumption by 6.26 PJ in 2017 when compared to 2007. Increasing passenger kilometers and decreasing energy consumption resulted in decreasing specific energy consumption. Increasing tourists directly increased passenger kilometers. The passenger kilometers increased by 44.16 percent when compared to 2007. In terms of fuel economy (kilometer per MJ), tuk-tuks had the highest fuel economy among the road passenger transport vehicles during 2007–2017 (OTP, 2012; Pollution Control Department, 2007). The energy consumption in tuk-tuks decreased by 0.69 PJ when compared to 2007.

In terms of emissions, GHG emissions decreased by 0.08 Mt CO_2eq in 2017, and accounted for 0.80 percent of AAGR (see Figure 8d) when compared to 2007. Compared to energy consumption, the growth of GHG emissions was less than energy by 1.78 times. In addition to the five factors, fuel share was one important factor. It decreased GHG emissions by 0.04 Mt CO_2eq in 2017. Due to promotion of LPG and CNG in tuk-tuks, consumption of both fuels increased by12.68 percent of total energy consumption in 2017. Increasing the share of cleaner fuels as alternative energy therefore decreased GHG emissions.

3.2.5. Taxi

Energy consumption in taxis increased by 23.96 PJ in 2017 (see Figure 7e). However, it extremely increased more than seven times between 2008 and 2009 because the government wanted to replace LPG taxis with CNG taxis. In addition, CNG price was subsidized resulting in increasing CNG consumption in taxis around 1.73 times when compared to 2008.

Lifetime of taxis for public service must not exceed nine years according to Thailand's traffic laws. Nevertheless, their specific energy consumption increased during 2007–2017. In Thailand, empty taxis always drive around and search for passengers. Although there was a policy to manage the service and provide parking areas for taxis, implementation was not successful, resulting in increased specific energy consumption.

The change in travel volume demand decreased energy consumption during the first five years of the period. However, it increased after 2011. The travel volume demand decreased energy consumption by 0.36 PJ in 2011 when compared to 2007, while energy consumption increased by 10.30 PJ when compared to 2011. In 2013, the travel volume demand speedily increased energy consumption around 3 times when compared to 2011. Due to increasing fuel prices of gasoline and diesel, the travel volume demand slightly increased during 2012–2014. When Grab and Uber companies launched new taxi businesses in 2013 by providing the online taxi booking at lower fares, the travel volume demand largely increased. The increased travel volume demand due to better management of the taxi service resulted in decreasing specific energy consumption, as well as increasing energy efficiency in taxis. Hence the energy consumption reduced by 6.17 PJ in 2017 when compared to 2007. The purchasing power increased energy consumption by 3.64 PJ in

2013 when compared to 2007. However, it decreased energy consumption by 7.9 PJ in 2017 when compared to 2013. As a result of law enforcement to improve public safety of taxi service since 2014, uncertified taxis were retired which resulted in increasing energy efficiency and decreasing energy consumption.

In terms of energy-related emissions, GHG emissions from taxis increased by 1.74 Mt CO_2eq in 2015 when compared to 2007 (see Figure 8e), but decreased by 0.33 Mt CO_2eq in 2017 when compared to 2015. Besides the five factors influencing energy consumption, fuel share also contributed to increasing GHG emissions in taxis due to the promotion of CNG. It increased GHG emissions by 0.15 Mt CO_2eq in 2017 when compared to 2007.

3.2.6. Bus

The energy consumption in buses increased by 6.67 PJ in 2017 when compared to 2007. However, it increased by 7.89 PJ in 2012 and then slightly decreased until 2017. The country's standard of living, travel volume demand and specific energy consumption were main factors affecting increasing energy consumption (see Figure 7f). In 2017, these factors increased energy consumption by 7.81 PJ while the purchasing power decreased energy consumption by 2.02 PJ. In Thailand, more than 80 percent of buses are operated by private companies. Increasing the country's standard of living results in increasing amount of energy consumption by 4.51 PJ in 2017.

Travel volume demand increased energy consumption by 1.73 PJ in 2017. However, it decreased in the beginning period of 2007–2010. In the same period, increasing diesel prices caused a reduction in public bus trips operated by private companies. Thus, the travel volume demand decreased by 1.45 PJ in 2010. Then, the government promoted and subsidized CNG. Thus, CNG consumption in 2017 shared around 48.04 percent of total energy consumption in buses and the remainder was diesel.

In addition, the government launched a policy on free public buses in Bangkok and nearby provinces during 2011–2014. The policy resulted in increasing public buses as well as the corresponding travel volume demand since 2011. As mentioned above, increasing travel volume demand increased energy consumption by 1.06 PJ in 2011 when compared to 2007. Then, the energy consumption increased by 1.72 PJ in 2014 when compared to 2011. However, after 2014, the travel volume demand slightly decreased because CNG prices were allowed to be floated.

In terms of emissions in buses during 2007–2017, GHG emissions increased by 0.41 Mt CO_2eq in 2012 when compared to 2007, but decreased by 0.41 Mt CO_2eq in 2017 when compared to 2012 (see Figure 8f). During 2014–2017, GHG emissions were almost unchanged due to success in the promotion of alternative energy. The fuel share decreased GHG emissions by 0.05 Mt CO_2eq in 2017 when compared to 2007 due to the promotion of low carbon fuels in buses, especially CNG. The emissions factors decreased GHG emissions by 0.04 Mt CO_2eq in 2017. The increase of biodiesel resulted in decreasing emissions factors. The proportion of biodiesel in diesel increased by 6.44 percent of diesel consumption in the same period.

3.3. Factors influencing road passenger transport by the LMDI-I analysis

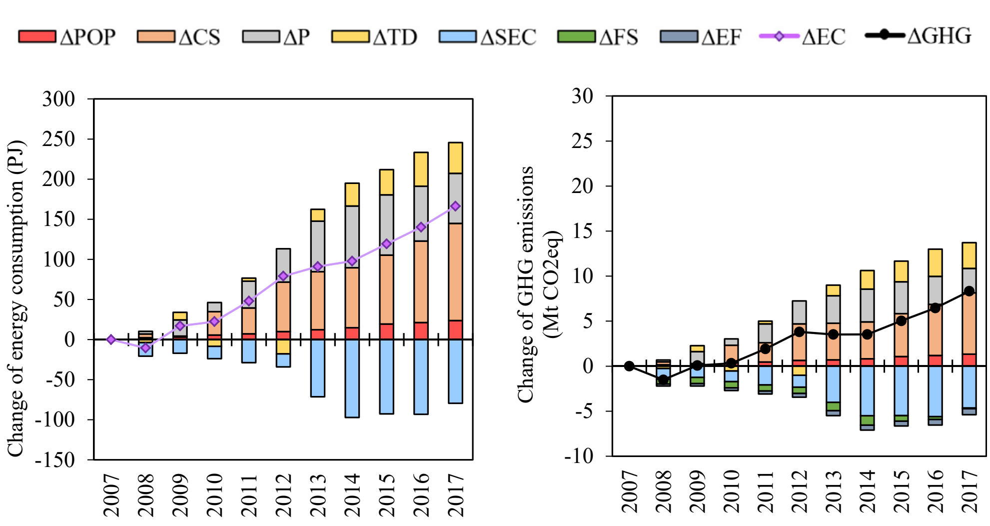
Energy consumption in road passenger transportation increased continually during 2007–2017 (see Figure 9a). However, it slightly decreased during 2007–2008 due to the economic crisis. During 2007–2017, factors of population, country's standard of living and purchasing power influenced increasing energy consumption while specific energy consumption was decreased. However, the travel volume demand was varied and uncertain.

The population had less impact on change of energy consumption. Population in Thailand slightly increased by around 0.03 percent per year. In 2017, the population impact on increasing energy consumption was 23.71 PJ when compared to 2007. Increasing population resulted in increasing energy consumption in all vehicle types, especially in sedans, vans and motorcycles.

Development of the country's standard of living, resulting in increasing GDP per capita, implies that higher income makes people more comfortable. In most developing countries, infrastructures of public transport are underdeveloped. Therefore, people always use private vehicles. In the case of Thailand, the country's standard of living played a major role in change of energy consumption. In particular, it increased energy consumption in road passenger transport by 121.03 PJ.

Generally, the purchasing power is related to the country's standard of living. The first car policy in Thailand during 2011–2013 increased purchasing power. The higher purchasing power resulted in increasing energy consumption, mainly in private vehicles such as sedans. In 2017, purchasing power increased energy consumption by 62.46 PJ when compared to 2007.

During 2007–2012, the fluctuation in travel volume demand mainly concerned sedans. Due to less developed public transport and the first car policy, private vehicles had the largest share, especially sedans. In 2012,



a) Energy consumption b) GHG emissions

Figure 9. Decomposition of energy consumption and GHG emissions in the road passenger transpotation.

travel volume demand decreased energy consumption by 17.95 PJ when compared to 2007. After 2012, improved safety and quality of public transport, along with the Grab taxi business, had major effects on energy consumption. In 2017, the travel volume demand increased energy consumption by 38.42 PJ when compared to 2007.

Specific energy consumption played a major role in decreasing energy consumption during 2007–2017. Energy consumption decreased by 79.41 PJ in 2017 when compared to 2007. The first car policy resulted in increasing the number of new sedans. However, specific energy consumption has resulted in decreasing energy consumption since 2013, mainly in vans, sedans and motorcycles.

In terms of energy-related emissions, Figure 9b illustrates the decomposition of GHG emissions for Thailand's road passenger transportation. GHG emissions increased by 8.33 Mt CO_2eq during 2007–2017. The change of GHG emissions followed the same trend as energy consumption, but growth of GHG emissions was lower than that of energy consumption by around 1.38 times. Factors of population, country's standard of living, purchasing power, and travel volume demand contributed to increasing GHG emissions by 13.72 Mt CO_2eq in 2017 when compared to 2007. In contrast, factors of specific energy consumption, fuel share and emissions contributed to decreasing GHG emissions by 5.39 Mt CO_2eq in 2017 when compared to 2007. Emission factors decreased GHG emissions due to substitution of biofuels for gasoline and diesel in the road passenger transportation. Sedans, vans and buses were the largest contributors to decreasing GHG emissions due to the lowering emissions factor of biofuels.

4. Conclusion

To understand the key relevant factors influencing energy consumption and energy-related emissions in Thailand's road passenger transport, this study employed the decomposition technique of the additive LMDI-I index method to analyze the influencing factors over the period of 2007–2017. The analysis investigates five influencing factors on energy consumption, namely, population, country's standard of living, purchasing power, travel volume demand and specific energy consumption, and two additional influencing factors on emissions, namely, fuel share and emission factors.

Results shows that energy consumption in the road passenger transport increased continually during 2007–2017, but it slightly decreased during 2007–2008 due to the economic crisis. During 2007–2017, population, country's standard of living, and purchasing power influenced increasing energy consumption. However, the travel volume demand was uncertain. Results also indicate that the increase of population and country's standard of living pushed purchasing power up. Moreover, when oil price increased during 2008–2015, Thailand established the Energy Efficiency Plan (EEP).

The growth of emissions was lower than energy consumption by around 1.38 times during 2007–2017. The factors of fuel share and emissions significantly decreased GHG emissions. The decrease of GHG emissions in fuel share shows the success of biofuels promotion in Thailand. In terms of emission factors, decreasing GHG emissions resulted from substitution of biofuels for gasoline and diesel in the road transport.

5. Recommendations for policy makers

Based on the results of this study, the policy implications on energy savings and energy-related emissions are as follows:

This policy on energy efficiency improvement will directly reduce energy consumption and emissions. The energy efficiency measures should be implemented in all vehicle types. Sedans are the largest share of vehicles in the road passenger transport. Taxis and buses have inefficient use of energy. Therefore, the government should set energy consumption standards, minimum energy performance standards or CO_2 emissions standards for newly registered vehicles, such as eco stickers. The implementation of mobile applications in the public transport system could reduce both energy consumption and emissions.

Results indicate that travel volume demand increased energy consumption and emissions, but it decreased the specific energy consumption during 2007–2017. Thus, increasing the number of passengers per trip or per vehicle resulted in decreasing specific energy consumption. Therefore, the government should motivate people to use public transport or increase the number of passengers per vehicle.

Biofuels can reduce emissions. Some vehicle types are limited to the use of biofuels. Therefore, incentives to use biofuels are recommended. Currently, the impact of EV is insignificant due to lack of EV information. However, in the long term, EV will play an important role in the transport sector. In addition, the fuels mix in power generation is very important. If electricity is produced from cleaner energy resources, emissions will be lower.

Declarations

Author contribution statement

Piti Pita: Performed the experiments.

Pornphimol Winyuchakrit: Conceived and designed the experiments; Analyzed and interpreted the data.

Bundit Limmeechokchai: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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