

## Passenger transportation sector gasoline consumption due to friction in Southeast Asian countries



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### ABSTRACT

Energy demand in the transportation sector across Southeast Asian (SEA) region is rapidly increasing. This poses a challenge to the sector in mitigating greenhouse gas (GHG) emissions because of its heavy reliance on fossil fuels. Decarbonisation efforts tend to focus on the use of low carbon energy, often neglecting frictional losses in vehicles. Therefore, the study aims to determine the fuel cost savings and the environmental impact from reduction of frictional energy losses in passenger cars and motorcycles for selected SEA countries. An energy analysis framework is proposed; estimating a total of USD 42.6 billion/year is wasted through fuel energy loss in moving these vehicles in the selected SEA countries, emitting 109 Mtonne/year of CO<sub>2</sub>. By implementing relevant tribological improvement strategies, fuel energy savings of USD 18.3 billion/year could be achieved, leading to 46.6 Mtonne/year of CO<sub>2</sub> emissions reduction. This level of CO<sub>2</sub> emissions reduction, obtained via friction reduction, can contribute between 0.8% and 1.9% towards the committed GHG reduction targets for the selected SEA countries by 2030. It is emphasised that combined effort, from vehicle manufacturers and end-users, is required in implementing relevant friction reduction strategies to avoid backlash from inappropriate use of these strategies.

### 1. Introduction

Global transportation energy demand is projected to increase up to around 155 quadrillion BTU (163 EJ) in the year 2040 from 104 quadrillion BTU (595 EJ) in the year 2012, representing a growth of 49% [1]. It is also projected that gasoline would remain as the largest transportation fuel at 33% in 2040 [1]. Such projection raises even more concern with regards to the effect of fossil fuel emissions on the environment. Therefore, it is important that countries, which participated in the 2015 United Nations Climate Change Conference (COP21), increase their effort to achieve their Intended Nationally Determined Contribution (INDC) towards green-house-gas (GHG) emissions reduction, in keeping the increase in global average temperature to well below 2 °C when compared with the pre-industrial era.

Most countries in Southeast Asian (SEA) region have announced INDCs relevant to the need of their countries to combat the rise of GHG emissions. The efforts put in by SEA countries are crucial in GHG emissions reduction because this region has a combined population that creates the world's third largest market, after China and India [2]. Besides this, in the year 2014, there are a total of 1.2 billion vehicles in

use (excluding motorcycles) in the world [3], with an estimated 33.1% of these vehicles found to be used in countries from Asia, Oceania and Middle East. From this, about 13.5% of the total vehicles in use are found in SEA region [3].

It is only essential that the transportation sector also undertake significant decarbonisation measures, as one of the major contributor towards global GHG emissions (up to 23% global CO<sub>2</sub> emissions from fuel combustion [4]). Decarbonisation in the transportation sector could include, but not limited to: (1) moving towards alternative fuels; (2) improving energy efficiency on vehicles and (3) using alternative lubricants. Such measures could prove to be a challenge to COP21 participating countries' success in achieving the levels of GHG emissions reduction committed in their announced INDCs because of the heavy reliance on fossil fuel products in this sector [5].

One of the common example of decarbonisation effort in switching to alternative fuels include blending of bioethanol with gasoline to be used in internal combustion (IC) engines, which has been shown to significantly reduce life cycle GHG emissions [6]. For IC engines running on diesel fuel, blending of biodiesel, derived from natural feedstocks, such as palm oil, with diesel fuel has been shown to be able to

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reduce life cycle GHG by 1.03 million tonnes in Malaysia [7]. In a separate study, it is estimated that CO<sub>2</sub> emissions in the transportation sector in Malaysia could be reduced between 6.7% and 15.1% by blending 5% biodiesel (B5) in diesel fuel and 10% bioethanol (E10) in gasoline fuel for use in vehicles running on IC engines [8].

Blending of biodiesel (e.g. soybean oil derived) with diesel fuel has been reported to reduce CO<sub>2</sub> emissions when used in IC engines [9]. However, there are also conflicting observations being reported in literature, showing increased CO<sub>2</sub> emissions, when biodiesel blended with diesel fuel is used to operate these engines [10,11]. Other studies have demonstrated that too high an amount of biodiesel blending with diesel fuel in IC engines could lead to significant engine lubricant dilution, generating increased friction and wear [12–14]. Some engine manufacturers even reported of possible premature engine failure as a result of higher levels of biodiesel dilution of the engine lubricant [15]. In addition to these, there are also concerns on corrosion of engine components being in direct contact with such biofuel, affecting durability of the engines [16].

Pongthanasawan and Sorapipatana [17] found that moving to alternative fuels does have higher GHG mitigation impact in the short term. However, they also stated that improving efficiency of vehicles could have higher GHG mitigation in the longer term, only with the condition that the penetration of high-energy efficiency technologies increases significantly. Therefore, alternatively, the transportation sector can also focus on using higher energy efficiency vehicles. This involves promoting the use of either fuel cell, solar photovoltaic system [18] or electric powered vehicles. In Japan, it is estimated that a reduction of CO<sub>2</sub> emissions by as much as 81% by the year 2050 when compared with the level in the year 1990 could be achieved, if the share of low emission vehicles, such as electric vehicles, reach 90% and 60% in passenger and freight transportations, respectively [19].

Egbue et al. [20] mentioned that increasing the penetration of electric vehicles heavily depends on: (1) the public's willingness to pay for the new technology; (2) the amount of distance that can be travelled using these vehicles; (3) the perception of these vehicles as being good for the environment and (4) the perception of these vehicles' travel speed. It is also essential that appropriate electric vehicle charging strategies be implemented using renewable energy sources [21–23]. However, some still believed that electric vehicles might take a while before being largely used across the globe due to its high vehicle and battery costs [5,24]. A recent study found that existing transportation infrastructure might still favour liquid alternative fuels over electricity or hydrogen [25]. The same study also mentioned that human nature of satisfying their needs with the least effort might also favour liquid fuels over electricity.

In view of these possible scenarios, alternative decarbonisation approaches should also be considered. The analysis by Zhao et al. [26] suggested that conventional powertrain for vehicles still has potential for energy conservation. Fuel economy standards for motor vehicles, where a minimum requirement for the energy performance of the vehicle that manufacturers must meet before it can be legally sold, have been identified as an effective strategy in reducing emissions [26–29]. One of the possible ways to conserve energy in vehicles includes reducing frictional energy losses in improving the vehicle fuel efficiency. Holmberg et al. estimated that one third of available fuel energy is actually being used to overcome friction in passenger cars [30]. By reducing frictional losses in passenger cars worldwide, it is possible to achieve fuel savings of up to 385 billion litres/year and CO<sub>2</sub> emissions reduction of up to 960 million tonnes/year.

In order to determine the impact of various possible decarbonisation efforts, a number of studies employed econometric models for energy planning analysis in estimating energy demand and CO<sub>2</sub> emissions in the transportation sector [17,31,32]. Some researchers adopted optimisation models to facilitate energy planning for this sector [8,33,34]. Typical economic quantities used are type of fuel mix, fuel price, income per capita and fuel consumption. However, such analysis

**Table 1**  
Estimated number of vehicles in use by type in selected Southeast Asian (SEA) countries in 2014.

Country	Number of vehicles in use (thousand units)			
	Passenger cars [3]	Commercial vehicles [3]	Motorcycles	Total
Indonesia	12,595	8278	92,976 [35]	113,849
Malaysia	11,027	1201	11,088 [36]	23,316
Philippines	3099	437	4489 [37]	8025
Singapore	648	179	144 [38]	971
Thailand	8381	7224	19,147 [39]	34,752

approaches lack the capacity to directly consider the effect of engineering technological advancements towards vehicle energy consumption improvements, such as friction losses reduction. For this, Holmberg et al. proposed a method to calculate energy consumption for passenger cars by breaking down the energy consumption into exhaust and cooling losses and mechanical power [30], allowing for more detailed inclusion of vehicle energy consumption measures.

In this study, the aim is to determine the financial savings and the environmental impact of frictional losses reduction in the SEA region transportation sector, which is often ignored in most energy analysis. Table 1 shows the breakdown of vehicle types in use in selected SEA countries. The three major types of vehicles include passenger cars, commercial vehicles and motorcycles. Overall, in the selected SEA countries, it can be observed that passenger cars and motorcycles are the two most common vehicles in use. In Fig. 1(a), passenger cars are observed to be the dominant type of vehicle in use in Singapore, which comprises 66.7% of the estimated total vehicles in use in this country. On the other hand, in Indonesia, approximately 81.7% of the vehicles in use are motorcycles. Similar observation can also be made for countries such as the Philippines and Thailand, where motorcycles contribute towards 55.9% and 55.1% of the estimated total vehicles in use in these countries, respectively. However, the number of passenger cars (47.3%) and motorcycles (47.6%) in use in Malaysia are evenly matched.

The information on commonly used fuel type by the transportation sector in SEA region is also critical when conducting the intended energy analysis. It is found that the fuel type typically used for motorcycles in these countries is gasoline. However, the same cannot be said for passenger cars in the selected SEA countries as depicted in Fig. 1(b). The passenger cars in most of these countries are observed to mainly run on gasoline fuels. However, diesel fuel usage for passenger cars in Indonesia, the Philippines and Thailand are shown to also be fairly significant. The other fuel types consumed by passenger cars considered in Fig. 1(b) include Compressed Natural Gas (CNG), electric, combination of gasoline and electric and combination of diesel and electric.

From Fig. 1, it can be surmised that the major types of vehicles in use in the selected SEA countries are passenger cars and motorcycles, predominantly running on gasoline fuel. Hence, the current energy analysis has chosen to focus on determining the gasoline fuel energy consumption by passenger cars and motorcycles in Indonesia, Malaysia, the Philippines, Singapore and Thailand. The financial savings and environmental impact from possible reduction of frictional energy losses for passenger cars and motorcycles are identified by adopting the framework proposed by Holmberg et al. [30].

## 2. Methodology

The energy analysis in the current study focuses on gasoline fuel energy usage by passenger cars and motorcycles in selected SEA countries. The breakdown of fuel energy consumed by each of these vehicle types has to first be determined in order to ascertain the relevant frictional energy losses. Fig. 2 illustrates the energy analysis framework adopted for the current study. The following sections

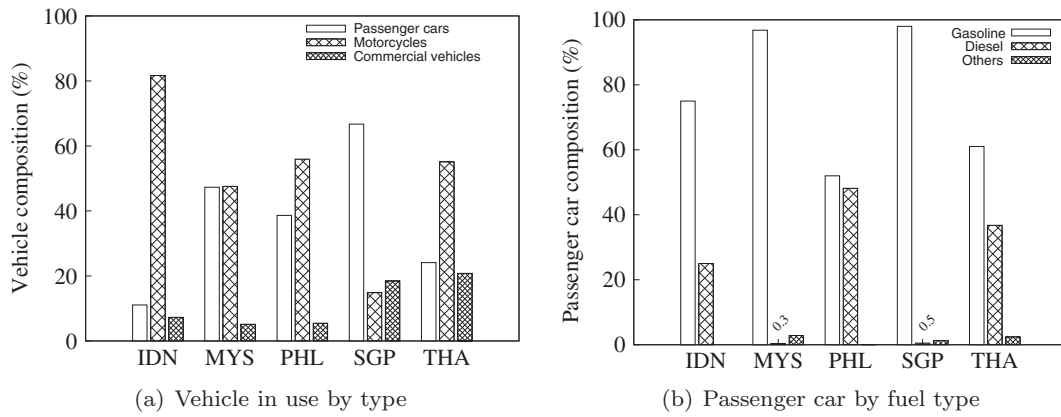


Fig. 1. Vehicle types in use for selected Southeast Asian (SEA) countries in 2014 [3,35–40].

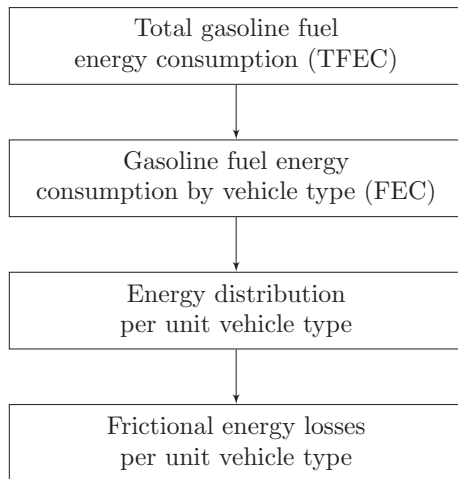


Fig. 2. Gasoline fuel energy analysis framework for passenger cars and motorcycles in selected Southeast Asian (SEA) countries.

explain the framework applied in the current study to determine and to identify frictional energy losses for passenger cars and motorcycles.

2.1. Total fuel energy consumption

The first step in the energy analysis is to determine the total gasoline fuel energy consumption by passenger cars and motorcycles for selected SEA countries. The latest statistical data for the consumption of these fuels by country in the transportation sector are obtained from International Energy Agency (IEA) [41]. Since passenger cars and motorcycles in most of the selected SEA countries operate on gasoline (see Fig. 1), the current energy analysis will focus on gasoline fuel energy consumption by the selected vehicle types. It is to note that with proper adaptation, the proposed framework can also be used to analyse energy consumption for different types of vehicles, running on fuels other than gasoline.

2.2. Fuel energy consumption by vehicle type

Using the total amount of gasoline fuel energy consumption in the transportation sector provided by IEA for each of the selected SEA countries, the breakdown of fuel energy consumption for passenger cars and motorcycles can be determined. In order to do so, the total gasoline fuel energy consumption (TFEC) for passenger cars corresponding to each of the selected SEA countries is first calculated as follow:

$$TFEC_{pc} = \frac{\text{No. of passenger cars}}{\text{No. of PCEU}} \times TFEC_{tot} \quad (1)$$

The term PCEU in Eq. (1) refers to a passenger car equivalent unit based on fuel energy consumption. This term is introduced to distinguish proportionally TFEC between passenger cars and motorcycles. In this analysis, the number of PCEU is calculated as:

$$\text{No. of PCEU (unit)} = \text{No. of passenger cars} + \text{FECE}/\text{No. of motorcycles} \quad (2)$$

where fuel energy consumption ratio (FECE) between a unit average passenger car and a unit average motorcycle is computed using:

$$FECE = \frac{\text{FEC per unit average passenger car}}{\text{FEC per unit average motorcycle}} \quad (3)$$

Then, the gasoline fuel energy consumption (FEC) per unit vehicle type can be determined based on the following relation [42]:

$$\begin{aligned} \text{FEC (kJ/unit/year)} &= \text{Fuel consumption (g/km)} \\ &\quad \times \text{Average Mileage (km/unit/year)} \times \text{LHV (kJ/g)} \end{aligned} \quad (4)$$

where LHV is the lower heating value for the fuel ( $\approx 43.7$  kJ/g for gasoline [42] with density for gasoline taken as 745 g/litre).

In the current analysis, gasoline fuel energy consumption ratio (FECE) between an average passenger car and an average motorcycle is estimated using vehicle specifications given in Appendix B. The average passenger car specification is based on the data by Holmberg et al. [30]. A slight adjustment is made from the referenced data in this study. Based on the average data provided by Global Fuel Economy Initiative (GFEI) from the year 2005 to 2014 [43], the average fuel consumption for passenger cars is approximately 0.08 l/km. However, typical fuel consumption values are derived from the New European Driving Cycle (NEDC), which is estimated to be on average 25% lower than the actual fuel consumption values when the vehicles are on the road [44]. This is because typical fuel consumption tests are often unrepresentative of real-world driving patterns/characteristics. Therefore, for this analysis, the average fuel consumption for passenger cars on the road is adjusted to be approximately 0.106 l/km.

For motorcycles, small and inexpensive motorcycles dominate the worldwide motorcycle demand (approximately 84% units of such vehicle sold in 2016), with China being the largest national market [45]. As an approximation for this study, the average motorcycle specification is derived from motorcycle production distribution by engine capacity [46]. Using the average engine capacity obtained, specifications for an average motorcycle is selected from available motorcycle models in the existing market. It should also be noted that the term motorcycle also covers moped and scooters. Hence, from the average vehicle specifications given in Appendix B, gasoline FEC for an average passenger car and an average motorcycle are approximated to be 42.3 GJ/unit and 5.5 GJ/unit, respectively. This results in an FECE of 7.7:1, indicating that on average, 7.7 units of motorcycle consume the amount of

gasoline energy equivalent of a passenger car. Therefore, TFEC for motorcycles can now be determined as:

$$TFEC_{mc} = TFEC_{tot} - TFEC_{pc} \tag{5}$$

### 2.3. Energy distribution per unit vehicle type

The energy from burned gasoline fuel is transferred into heat and mechanical energy to move the vehicle. With known fuel energy consumption, it is now possible to map the energy distribution for passenger cars and motorcycles, operating on gasoline fuel. To investigate the fuel energy breakdown for a passenger car and a motorcycle, fuel energy consumption is taken to be affected by three major factors: (1) mechanical losses; (2) exhaust gases and (3) cooling. The proportion of energy breakdown is computed using the average vehicle specifications given in Appendix B. Generally, energy consumption due to mechanical losses in both passenger cars and motorcycles can be further divided into frictional losses and air drag losses. In this analysis, the energy loss due to air-drag while the vehicle is on the road is calculated as follow:

$$\text{Air drag} = \frac{\rho C_d}{2} \times A_f \times v^3 \times \frac{D_a}{v} \tag{6}$$

where  $\rho$  is the air density ( $\approx 1.2 \text{ kg/m}^3$ ). For frictional losses, there are four major contributors, namely: (1) rolling resistance, (2) engine frictional losses, (3) transmission losses and (4) brake losses. Each of the energy losses are calculated using the equations given below.

$$\text{Rolling resistance} = mv g C_r \times \frac{D_a}{v} \tag{7}$$

$$\text{Engine frictional losses} = \eta_{th} \times \text{FEC per unit vehicle} - P_{out} \times \frac{D_a}{v} \tag{8}$$

$$\text{Transmission losses} = (1 - \eta_{tr}) \times P_{out} \times \frac{D_a}{v} \tag{9}$$

$$\text{Braking losses} = 0.2 \times P_{out} \times \frac{D_a}{v} \tag{10}$$

Through this analysis, most of the fuel energy is shown to be wasted as a result of thermal losses from exhaust gasses and cooling of the IC engines. From the average passenger car and the average motorcycle specifications given in Appendix B, energy distribution for the respective transportation modes are determined and summarised in Figs. 3 and 4. It can be observed that frictional energy losses are approximated to take up 35.7% and 26.0% of the total fuel energy available for a passenger car and a motorcycle, respectively. This leaves on average only 17.5% and 17.3% of the total fuel energy that are used to move the passenger car and the motorcycle.

Frictional losses are as a result of opposing surfaces sliding against each other. Lubrication is often introduced to reduce such losses. In this study, engine frictional losses are distributed based on the mechanical performance of the engine subsystems, focusing mainly on their respective lubrication systems. The performance of a lubrication system or a tribological system can be examined using a typical lubrication Stribeck curve, which illustrates the various operating lubrication regimes when two opposing surfaces are in relative motion [47,48]. A typical lubrication Stribeck curve is given in Fig. 5, showing the various lubrication regimes involved in a lubrication system. From this characteristic curve, the coefficient of friction (CoF) generated along the lubricated conjunction is shown to vary with lubricant viscosity, sliding velocity and also applied normal load.

Using the principles of the lubrication Stribeck curve in Fig. 5, frictional energy losses in passenger cars and motorcycles can be further broken down based on the major systems in the vehicles, corresponding to their relevant operating lubrication regimes. The lubrication regimes considered in this analysis include: boundary lubrication (BL), mixed lubrication (ML), elastohydrodynamic lubrication for sliding motion (EHL-S), elastohydrodynamic lubrication for combined sliding and rolling motion (EHL-SR), elastohydrodynamic lubrication for rolling motion (EHL-R) and hydrodynamic lubrication (HL). The pumping and viscous losses (VS), referring to the resistance of the fluid towards viscous shearing taken at a temperature of 80 °C [30], are also taken into consideration in the current analysis.

Frictional losses in passenger cars (see Fig. 3) and motorcycles (see Fig. 4) mainly originate from the engine and the transmission. From these two systems, engine friction is considered one of the major friction contributors for both transportation modes. Assuming that suitable and manufacturer recommended engine lubricants are used in the respective transportations, the frictional energy losses in an engine for an average passenger car and an average motorcycle are composed of the following [30]:

- 45% engine in-cylinder friction.
- 30% bearings and seals (HL).
- 15% valve train (ML).
- 10% pumping and viscous losses (VS).

Engine cylinder friction is heavily affected by the sliding of piston ring pack against the engine cylinder liner. The sliding speed of the ring pack varies across the location along the cylinder liner, which has minimum value around the dead centres and maximum value around mid-stroke span [49]. Therefore, the lubrication regimes affecting engine in-cylinder friction the most are HL and EHL-S. Along these lubrication regimes, engine lubricant properties play a significant role in

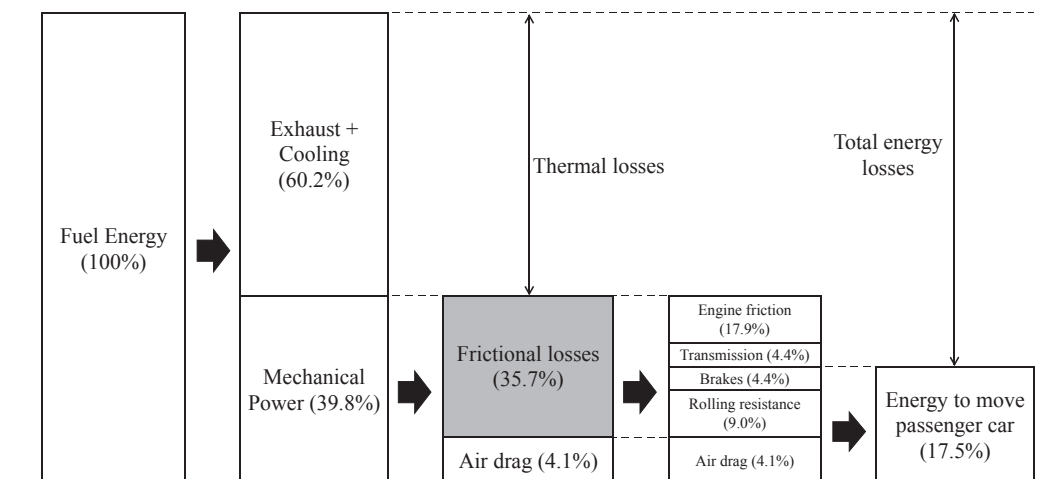


Fig. 3. Gasoline fuel energy distribution for a unit average passenger car.

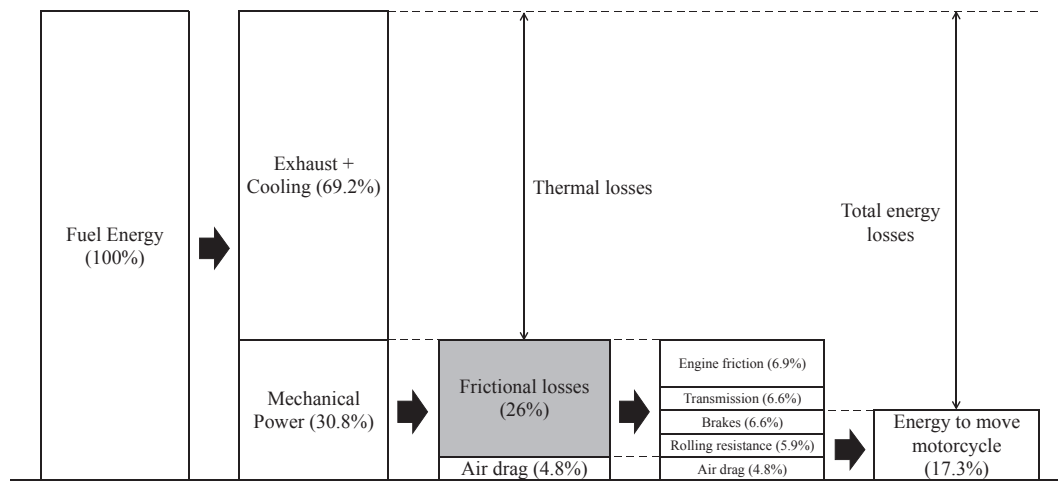


Fig. 4. Gasoline fuel energy distribution for a unit average motorcycle.

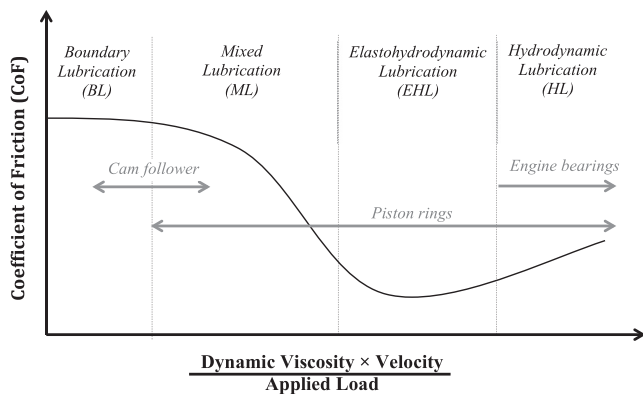


Fig. 5. A typical lubrication Stribeck curve.

affecting fluid film lubrication performance. From the frictional energy distribution given above, engine in-cylinder friction can be further broken down based on lubrication regimes given below [30]:

- 40% HL.
- 40% EHL-S.
- 10% ML.
- 10% BL.

As for transmission frictional losses, the gear pair coming in and out of contact during operation affects the lubrication performance of the contact. The gear pair contact is typically highly loaded, leading to a harsher lubrication environment that is typically along EHL to ML regime [50]. Therefore, the frictional components based on lubrication regimes for a typical transmission for passenger cars and motorcycles can be broken down as follow [30]:

- 20% VS.
- 55% EHL-SR.
- 20% EHL-R.
- 5% ML.

With estimated frictional energy losses, the study then applies the predicted tribological improvement trends proposed by Holmberg et al. [30]. They estimated tribological improvements up to the year 2020 for passenger cars. The tribological trend is illustrated in Fig. 6, showing CoF levels at different lubrication regimes and rolling resistance (TR) for passenger cars from the year 2000 to the year 2020. The pumping and viscous losses (VS) are represented by the secondary vertical axis in

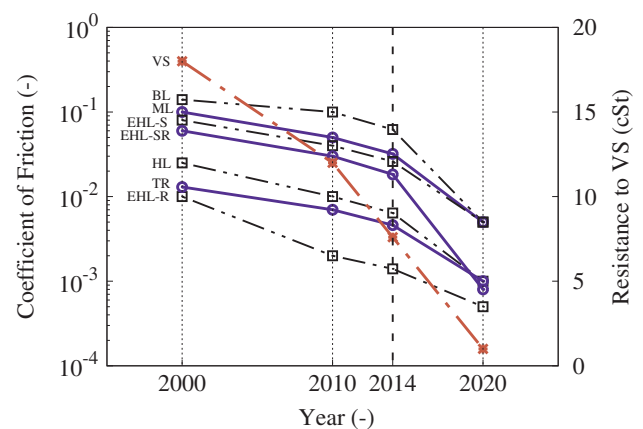


Fig. 6. Tribological improvement trends for passenger cars and motorcycles (VS-Viscous losses; BL-boundary lubrication; ML - mixed lubrication; EHL-S - elastohydrodynamic lubrication for sliding; EHL-SR - elastohydrodynamic lubrication for sliding and rolling; EHL-R - elastohydrodynamic lubrication for rolling; HL - hydrodynamic lubrication; TR - Tire rolling).

Fig. 6. The CoF levels predicted for passenger cars in the year 2020 is based on the estimations by the best and renowned experts in the field of tribology [30]. A similar approach has also been implemented to study friction reduction on commercial vehicles, such as trucks and busses [51]. As an initial approximation for the current energy analysis, the potential tribological improvements for motorcycles are assumed to follow the improvements for passenger cars.

### 3. Results and discussions

The study now proceeds to determine gasoline fuel energy consumption by passenger cars and motorcycles in Indonesia, Malaysia, the Philippines, Singapore and Thailand. The energy analysis framework, as proposed in Fig. 2, is adopted to analyse frictional energy losses for the selected modes of transportation. The analysis also discusses on the reduction of frictional energy losses and its financial savings and environmental impact from tribological improvements predicted by Holmberg et al. [30].

#### 3.1. Energy analysis for selected SEA countries

In order to verify the proposed framework, the energy consumption for passenger cars and motorcycles in Singapore using available statistical information provided by Singapore’s Land Transport Authority (LTA) [38], are used as verification data. The calculation requires

**Table 2**  
Average mileage per year by vehicle type for Singapore in 2014.

Vehicle type	Estimated mileage (km/year)	Reported mileage (km/year) [38]	Deviation (%)
Passenger car	18,050	17,500	3.1
Motorcycle	13,000	12,800	1.6

information with regards to the number of passenger cars and motorcycles in use to determine the total number of PCEU as stated in Eq. (1). Using the distribution of gasoline fuel energy consumption obtained above, the fuel energy utilised by a unit passenger car and a unit motorcycle in Singapore is estimated to be 58.8 GJ/unit and 7.6 GJ/unit. These energy usages correspond to an estimated mileage of 18,050 km/year for a unit passenger car and 13,000 km/year for a unit motorcycle. It can be observed that the estimation from the proposed framework is below 5% deviation when compared with the estimated mileage (see Table 2). Hence, it can be surmised that the framework proposed in this study is capable of reasonably estimating energy consumption for passenger cars and motorcycles.

Fig. 7(a) shows the fuel energy consumption by the transportation sector in the selected SEA countries. It can be observed that the transportation sector in Indonesia consumes the highest amount of gasoline fuel when compared with the other SEA countries. The amount of gasoline energy consumption in Indonesia is approximately 52.1% of the total gasoline usage by all the selected SEA countries. This is followed by Malaysia (26.8%), Thailand (12.2%), the Philippines (6.9%) and Singapore (2.0%). It is to note that for the Philippines, Singapore and Thailand; gas/diesel fuel energy consumption is higher than gasoline fuel energy consumption. Gas/diesel fuel, as defined by IEA, refers to heavy gas oils, which distil between 380 °C and 540 °C while gasoline refers to the light hydrocarbon oil used as fuel for land-based spark ignition engines, such as motor vehicles [41]. It is also highlighted in Fig. 7(b) that Malaysia has the highest energy consumption per capita. Malaysia uses more gasoline per capita by around 4, 16, 11 and 5 times more than Indonesia, the Philippines, Singapore and Thailand, respectively.

As mentioned above, the study focuses on gasoline fuel energy consumption for passenger cars and motorcycles. This is because, for the selected SEA countries, these two modes of transportation mostly run on gasoline fuel (see Fig. 1). Therefore, from this point onwards, only gasoline fuel energy consumption is considered.

The average passenger car equivalent unit (PCEU) distribution based on gasoline fuel energy consumed by passenger cars and motorcycles in the selected SEA countries is given in Fig. 8. Approximately 97.1% of the gasoline fuel in Singapore is shown to be consumed by passenger cars, in-line with the country being a passenger car dominant country by number of vehicle in use (see Fig. 1). A similar observation

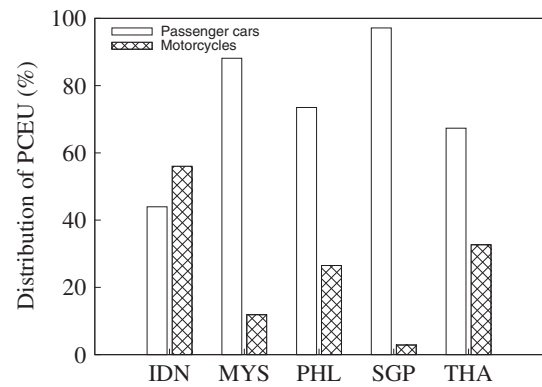


Fig. 8. Average passenger car equivalent unit (PCEU) distribution by vehicle type for selected Southeast Asian (SEA) countries in 2014.

can be made of Indonesia, which is a motorcycle dominant country, where fuel consumption by motorcycles is approximately 12.1% more than passenger cars in this country. However, the logic based on number of vehicles in determining energy usage dominance is not valid for countries such as Malaysia, the Philippines and Thailand. It can be observed that in Malaysia, 88.1% of the gasoline fuel energy is consumed by passenger cars with the remainder of 11.9% consumed by motorcycles in this country. This is in stark contrast when compared with the nearly equal numbers of passenger cars and motorcycles in use in this country.

Using energy consumption for each of the transportation modes, the average mileage for a unit passenger car and a unit motorcycle are estimated as in Fig. 9(a) for the selected SEA countries. The Philippines is shown to have the highest average mileage for a passenger car, with 19,200 km/year. This is followed by Singapore, Indonesia, Malaysia and Thailand. The same trend can also be mentioned about the average mileage for a unit motorcycle with the Philippines and Thailand having the highest and the lowest mileage of 13,800 km/year and 7100 km/year, respectively. From the estimated average mileage, Fig. 9(b) shows the total fuel energy consumed by passenger cars and motorcycles in the selected SEA countries. Motorcycles in Indonesia are shown to utilise the most energy when compared with other countries. The fuel energy consumed by motorcycles in Indonesia is approximated to be 577,000 TJ, which is 1.3 times of the energy consumed by the passenger cars in this country. For passenger cars, Malaysia contributed the most fuel energy consumption, with 469,000 TJ. This amount of fuel energy consumption is approximately 8 times higher than the fuel energy consumed by motorcycles in this country.

From the fuel energy available, a significant amount is dissipated as heat, leaving less than half of the energy being used to overcome friction and to move the vehicle. The total fuel energy loss in passenger

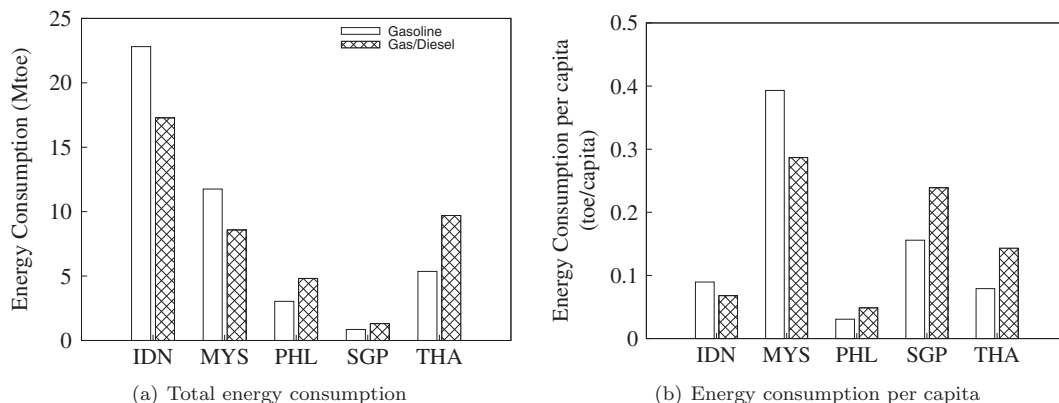


Fig. 7. Fuel energy consumption by transportation sector for selected Southeast Asian (SEA) countries in 2014 [41].

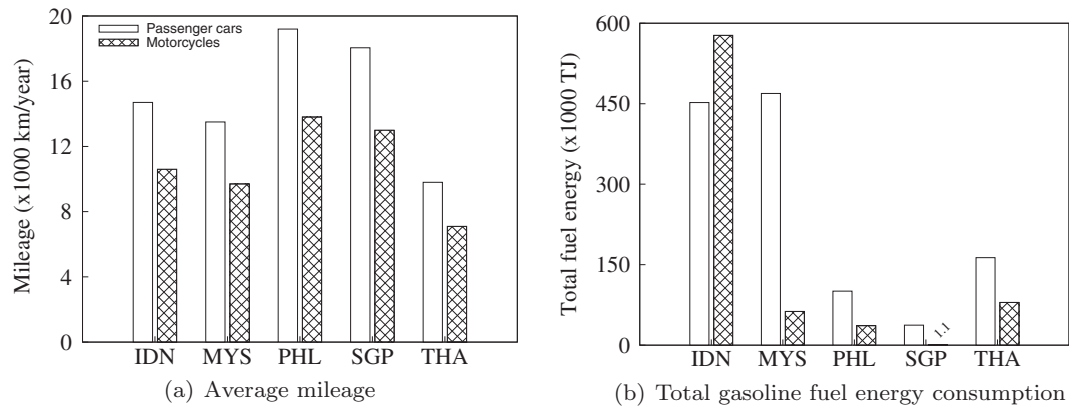


Fig. 9. Gasoline fuel energy consumption by vehicle type for selected Southeast Asian (SEA) countries in 2014.

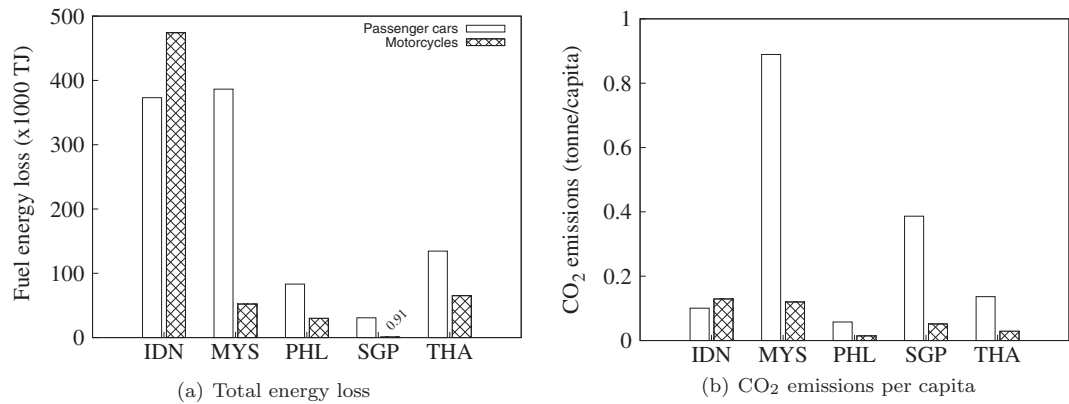


Fig. 10. Fuel energy loss by vehicle type for selected Southeast Asian (SEA) countries in 2014 (Population given in Appendix C).

cars and motorcycles for the selected SEA countries is given in Fig. 10(a). The total energy loss considers exhaust and cooling losses together with engine and transmission frictional losses (see Figs. 3 and 4). CO<sub>2</sub> emissions per capita based on total energy loss estimated for passenger cars and motorcycles are given in Fig. 10(b). From this analysis, it can be observed that Malaysia contributes the highest CO<sub>2</sub> emissions per capita for passenger cars (0.9 tonne/capita), while Indonesia contributes the highest CO<sub>2</sub> emissions per capita for motorcycles (0.1 tonne/capita). The total CO<sub>2</sub> emissions per capita in Malaysia as a result of fuel energy loss in both of these vehicles in use (1 tonne/capita) is approximately 13.5% of the total CO<sub>2</sub> emissions per capita generated in the country in 2014 (7.4 tonne/capita based on fuel combustions only [41]). The total amount of CO<sub>2</sub> emissions per capita generated in Malaysia is also observed to be 2.5 times more than the next highest contributor, which is Singapore with a total of CO<sub>2</sub> emissions per capita at 0.4 tonnes/capita.

Table 3 summarises the estimated costs as a result of fuel energy loss for both passenger cars and motorcycles in the selected SEA countries. The cost of fuel energy loss from motorcycles in Indonesia is the highest of any of the selected SEA countries for both modes of transportation,

estimated at USD 12.6 billion/year, which is approximately 1.4% of the country’s gross domestic product (GDP) in 2014. This results in CO<sub>2</sub> emissions of 32.8 Mtonne/year (see Table 4). For Malaysia, the cost of energy loss from passenger cars outweighs the amount from motorcycles by as much as USD 6.8 billion/year. It is to note that the cost of energy loss from passenger cars in Malaysia contributes to an estimated 2.3% of the country’s GDP. This leads to an estimated loss of USD 301 per person in Malaysia as a result of fuel energy loss. Using the same parameter, Singapore could have an estimated cost saving as a result of fuel energy loss of USD 298 per capita. However, the high amount is due to Singapore having the highest gasoline price in the region at USD 1.60/l. The total cost wasted to overcome friction in passenger cars and motorcycles in the selected SEA countries amounts to USD 42.6 billion/year, resulting in CO<sub>2</sub> emissions as much as 109 Mtonne/year.

### 3.2. Tribological impact towards frictional energy loss

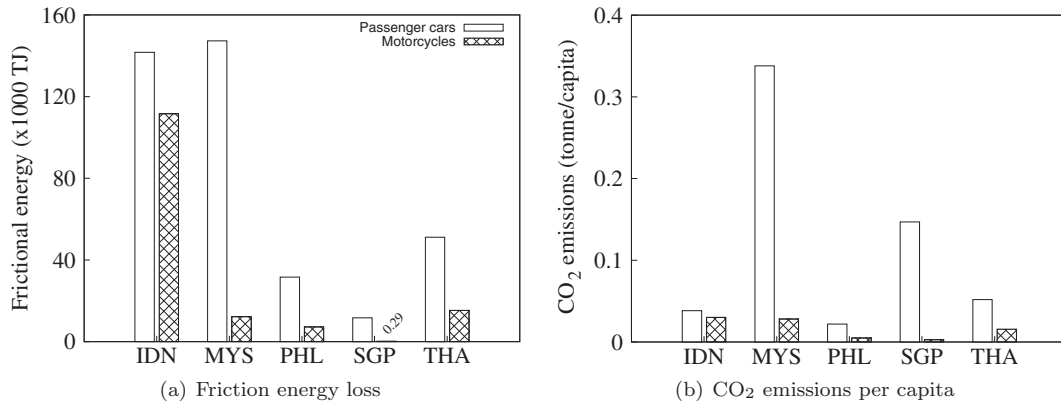
In this section, the impact of possible tribological improvements towards the energy losses from passenger cars and motorcycles for the selected SEA countries are estimated. From Figs. 3 and 4, it is estimated

Table 3  
Estimated cost as a result of fuel energy loss by vehicle type for selected Southeast Asian (SEA) countries in 2014 (Gasoline price/litre given in Appendix C).

Country	Cost (USD billion/year)			Cost (USD/year/capita)		
	Passenger car	Motorcycles	Total	Passenger car	Motorcycles	Total
Indonesia	9.8	12.6	22.4	38.6	49.4	88.0
Malaysia	7.9	1.1	9.0	265.0	36.0	301.0
Philippines	2.7	0.7	3.4	27.0	6.7	33.7
Singapore	1.4	0.2	1.6	263.0	35.0	298.0
Thailand	5.1	1.1	6.2	75.5	16.2	91.7

**Table 4**  
Estimated CO<sub>2</sub> emissions as a result of fuel energy loss by vehicle type for selected Southeast Asian (SEA) countries in 2014.

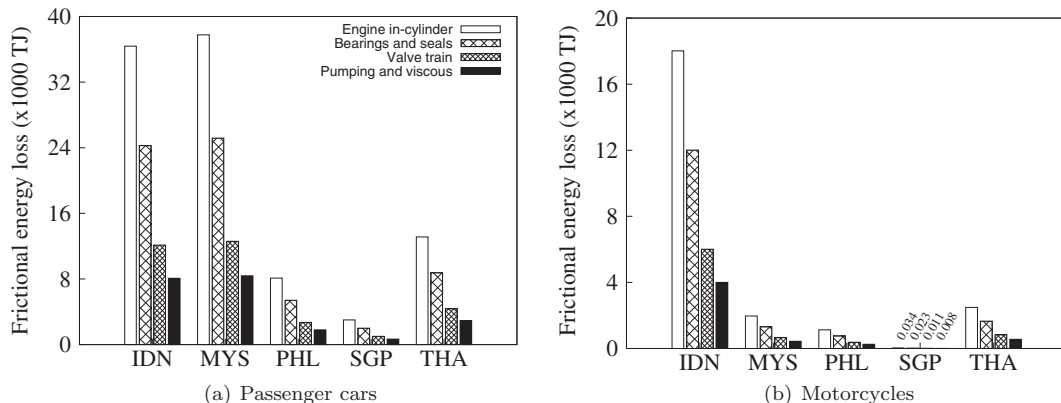
Country	CO <sub>2</sub> emissions (Mtonne/year)			CO <sub>2</sub> emissions (kg/year/capita)		
	Passenger car	Motorcycles	Total	Passenger car	Motorcycles	Total
Indonesia	25.6	32.8	58.4	101.0	129.0	230.0
Malaysia	26.6	3.6	30.2	890.0	120.0	1010.0
Philippines	5.7	1.4	7.1	57.6	14.4	72.0
Singapore	2.1	0.3	2.4	387.0	51.0	438.0
Thailand	9.2	2.0	11.2	137.0	29.0	166.0



**Fig. 11.** Friction energy loss by vehicle type for selected Southeast Asian (SEA) countries in 2014 (Population given in Appendix C).

that 35.7% and 26.0% of the fuel energy are consumed to overcome friction in passenger cars and motorcycles, respectively. The frictional energy losses in this study include engine friction, transmission friction, rolling resistance and braking losses. Fig. 11(a) gives the estimated frictional energy loss in passenger cars and motorcycles for the selected SEA countries. CO<sub>2</sub> emissions per capita as a result of frictional energy loss are also illustrated in Fig. 11(b).

In order to adopt the tribological improvement trend given in Fig. 6, frictional losses for passenger cars and motorcycles need to be first broken down into different components. For both passenger cars and motorcycles, the highest friction component is engine friction. The frictional losses from the engine come from: (1) engine in-cylinder losses, (2) bearings and seals losses, (3) valve train losses and (4) pumping and viscous losses. Fig. 12 illustrates the frictional energy losses in engines for passenger cars and motorcycles in the selected SEA countries. It is shown in Fig. 12 that the engine in-cylinder generates the most friction. The second largest frictional losses from an engine come from bearings and seals, which consistently operates along the HL regimes. This is then followed by the valve train system, often operating under mixed lubrication (ML) regime [52].



**Fig. 12.** Total frictional energy distribution by vehicle type for selected Southeast Asian (SEA) countries.

The distribution of engine in-cylinder frictional losses is given in Fig. 13 for passenger cars and motorcycles for selected SEA countries. Losses in engine in-cylinder due to hydrodynamic lubrication (HL) and elastohydrodynamic lubrication under pure sliding motion (EHL-S) are shown to be the highest contributors. This is expected because within an engine, the sliding between piston ring pack and engine cylinder liner is most often under the fluid film lubrication regime. The ring-liner contact will undergo mixed and boundary lubrication only along the top and bottom dead centres within the cylinder liners, where piston motion reversals occur [49].

The next major contributor towards frictional energy losses in passenger cars and motorcycles is from the transmission system. Using the frictional distribution provided above, the transmission frictional losses by lubrication regimes for passenger cars and motorcycles are shown in Fig. 14 for each of the major SEA countries.

It is acknowledged by Holmberg et al. that complete implementation of the estimated CoF reduction levels as given in Fig. 6 would be costly [30]. Therefore, for a more realistic estimation, Holmberg et al. assumed that only 50% of the friction reduction level be achieved by the year 2020. For this analysis, the losses due to air drag and braking



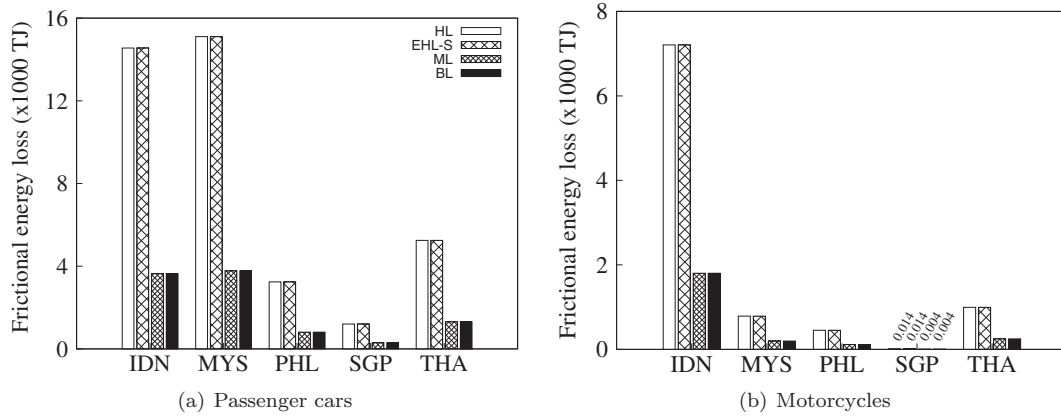


Fig. 13. Engine in-cylinder friction energy distribution by vehicle type for selected Southeast Asian (SEA) countries.

are assumed to remain constant. Reduced frictional losses will result in lower energy demand from passenger cars and motorcycles. Thus, this will produce a lower thermal energy loss from exhaust gasses and cooling of the engines. Using the more realistic estimation by Holmberg et al. [30], energy savings, as a result of tribological improvements towards frictional losses, from the exhaust gasses and cooling of the engines running on passenger cars and motorcycles, are approximated to be 37.2% and 35.2%, respectively.

Assuming that only half of the tribological improvement based on Fig. 6 be achieved, this will lead to a total cost savings for the selected SEA countries as given in Table 5. It can be observed that Indonesia stands to benefit the most from tribological improvements implemented for both passenger cars and motorcycles, with an estimated total cost savings of USD 9140 million/year. This is followed by Malaysia, Thailand, the Philippines and finally Singapore. The estimated fuel energy savings by each of the transportation modes for the selected SEA countries are given in Fig. 15. Malaysia and Indonesia are seen to be the countries gaining the most from such implementation of tribological improvements, saving up to a combined total of 534,000 TJ.

From an environmental point of view, the impact of tribological improvements on passenger cars and motorcycles for the selected SEA countries is summarised in Table 6. Indonesia is estimated to be able to reduce the most CO<sub>2</sub> emissions as compared to the other countries, with a total of 23,900 ktonne/year. On the other hand, Malaysia is shown to be the major beneficiary with respect to CO<sub>2</sub> emissions from passenger cars (11,400 ktonne/year). The reduction in CO<sub>2</sub> emissions from the selected SEA countries could total up to 46.6 Mtonne/year. As for CO<sub>2</sub> emissions per capita, it is shown in Fig. 16 that Malaysia could experience the most CO<sub>2</sub> reduction per capita, with a total reduction of 380 kg/capita per year. Such amount of reduction is approximately 5.8% reduction from the total CO<sub>2</sub> emissions per capita in Malaysia

Table 5

Estimated realistic cost savings (USD million/year) by vehicle type for selected Southeast Asian (SEA) countries (Gasoline price/liter given in Appendix C).

Country	Cost savings (USD million/year)		
	Passenger car	Motorcycles	Total
Indonesia	4210	4930	9140
Malaysia	3400	420	3820
Philippines	1150	380	1530
Singapore	620	17	637
Thailand	2200	980	3180

when compared with the level in 2014. The total CO<sub>2</sub> emissions reduction per capita when compared with the levels in 2014 for passenger cars and motorcycles in the selected SEA countries are tabulated in Table 7.

Prior to COP21 in Paris, countries that signed up for the United Nations Framework Convention on Climate Change (UNFCCC) were requested to announce their INDC towards GHG reduction target by the year 2030. The INDC committed by each of the countries is in effort to keep the increase in global average temperature to well below 2 °C as compared to the pre-industrial era. The announced unconditional INDC for the selected SEA countries included in this study is summarised in Table 8. In all the INDCs from selected SEA countries, they include the transport sector either directly or as part of the energy sector. Most of the transport-related options to reduce GHGs are based on existing policies and national policies. As most of the national policies did not include tribological improvements as part of their core strategies, it is essential to also assess the contributions from CO<sub>2</sub> emissions reduction, as a result of tribological improvements for passenger cars and

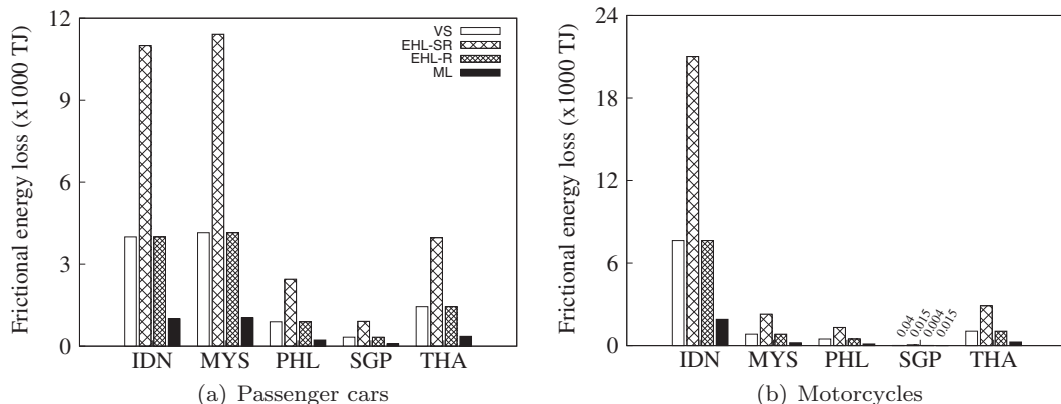


Fig. 14. Transmission friction energy distribution by vehicle type for selected Southeast Asian (SEA) countries.

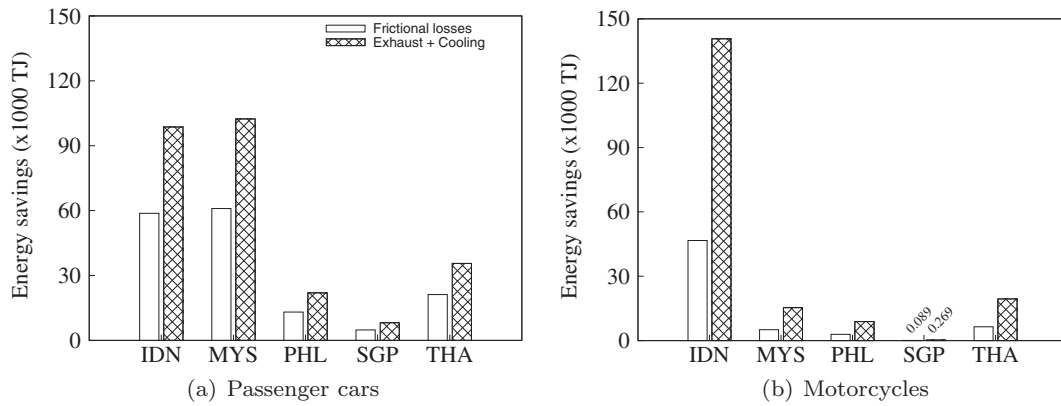


Fig. 15. Energy savings for passenger cars and motorcycles for selected Southeast Asian (SEA) countries.

Table 6

Estimated realistic reduction of CO<sub>2</sub> emissions (ktonne/year) by vehicle type for selected Southeast Asian (SEA) countries.

Country	CO <sub>2</sub> emissions reduction (ktonne/year)		
	Passenger car	Motorcycles	Total
Indonesia	11,000	12,900	23,900
Malaysia	11,400	1400	12,800
Philippines	2450	810	3260
Singapore	908	25	933
Thailand	3970	1780	5750

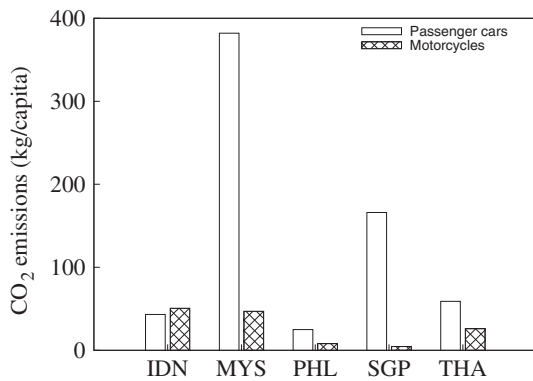


Fig. 16. Estimated realistic reduction of CO<sub>2</sub> emissions per capita by vehicle type for selected Southeast Asian (SEA) countries (Population given in Appendix C).

Table 7

Estimated realistic total reduction of CO<sub>2</sub> emissions per capita (kg/capita) when compared with the levels in 2014 for selected Southeast Asian (SEA) countries (Population given in Appendix C).

Country	CO <sub>2</sub> emissions per capita reduction (kg/capita)		
	Estimated reduction	Total [41]	% Reduction
Indonesia	94.0	1720	5.5
Malaysia	429.0	7370	5.8
Philippines	33.0	970	3.4
Singapore	171.0	8290	2.1
Thailand	85.0	3600	2.4

motorcycles in the selected SEA countries, towards the commitments by these countries. From Table 8, it is determined that the contribution towards INDC’s GHG reduction target through friction reduction of the studied vehicles range from 0.8% to 1.9%. Malaysia is shown to be the country that will gain the most by implementation of friction reduction strategies on passenger cars and motorcycles.

### 3.3. Tribological improvement strategies in friction reduction

In order to achieve the estimated friction reduction discussed above, Holmberg et al. outlined a number of known technical solutions that could be implemented [30]. Either the vehicle manufacturers or end-users currently in use could implement the solutions for friction reduction. The tribological strategies discussed in the following sub-sections could deliver financial savings and the environmental impacts as observed through the current analysis if implemented correctly.

#### 3.3.1. Vehicle manufacturers

For vehicle manufacturers, the solutions to reduce friction in passenger cars and motorcycles running on gasoline fuels will have to be implemented through new design solutions before the vehicles are delivered to the vehicle end-users. Such solutions typically include the need to alter the properties of rubbing surfaces in engine components. One of the approach is to utilise low friction coatings, such as diamond-like carbon (DLC) and Molybdenum disulfide (MOS<sub>2</sub>), which have been shown to be capable of reducing CoF of dry and lubricated sliding contacts by as much as 90% [53]. The significant CoF reduction achieved with the use of low friction coatings are essential for lubricated conjunctions, especially where direct surface-to-surface asperity contact is expected to be the main underlying mechanism of friction along ML and BL regimes.

Alternatively, vehicle manufacturers could opt to introduce surface textures/patterns on surfaces of engine components. A significant amount of research has been conducted to reduce friction especially along piston ring and engine cylinder liner conjunction through control of surface finishing and modifications. Initially, engine cylinder liner surfaces have high peaks of surface asperities, which have to be worn down through a “run-in” process. With the precision of modern surface finishing techniques, “run-in” liner surfaces can now be created through a three-stage honing process: (i) boring (formation of the bore), (ii) base or coarse honing and (iii) plateau honing [54].

Early studies have shown that having microasperities, such as dimples or even grooves, will impede lubricant flow, increasing lubricant film thickness and reducing friction [55–57]. Aside from plateau honing, well-designed surface texturing on either the engine cylinder liner or the piston ring itself have been shown to be able to reduce friction. Ryk et al. [58], Etsion [59] and Ryk and Etsion [60] found that friction reduction of around 25% along the piston ring-liner contact could be achieved by introducing micro-dimples along the surface of the piston ring itself. The micro-dimples on the ring surface are deposited using Laser Surface Texturing (LST) technique [58]. These micro-dimples along the ring surface provide micro-reservoirs that will enhance the lubricant retention along the contact. Rahnejat et al. also showed that by adding laser surface textures along the top dead centre region of the engine cylinder liner, an engine torque performance gain of roughly 4.5% could be achieved [61].

**Table 8**  
Climate contributions for selected Southeast Asian (SEA) countries during the 2015 United Nations Climate Change Conference (COP21).

Greenhouse gas (GHG) reduction target by 2030 as per the Intended Nationally Determined Contribution (INDC)							
Country	Base year data	Base year CO <sub>2</sub> Emissions (Mtonne)	Projected year	Projected CO <sub>2</sub> Emissions (Mtonne) BAU	Transport sector included	Unconditional reduction	Friction reduction contribution (%)
Indonesia	2010	–	2030	2881	Yes	Reduce emissions 29% below BAU by 2030	0.8
Malaysia	2005	288.66	–	–	Yes	Reduce GHG emissions intensity of GDP by 35% by 2030 relative to emissions intensity of GDP in 2005	1.9
Singapore	2005	40.9	–	–	Yes	Reduce emissions intensity by 36% from 2005 levels by 2030	1.3
Thailand	2005	–	2030	555	Yes	Reduce GHG emissions by 20% from the projected BAU level by 2030	1.1

### 3.3.2. Vehicle end-user

For vehicle end-users, the solutions for friction reduction mainly involve the use of better and suitable lubricants for the engine components. It has been shown in this study that oils lubricate most of the rubbing surfaces of the engine components. The formulation of these oils, for example, engine lubricants, consists of a significant amount (up to 95%) of base oil and a small percentage of additives [62–64]. The additive package is added to base oils to achieve specific performance-improving characteristics. The most commonly used additives are: detergent, dispersant, corrosion inhibitors, extreme-pressure and anti-wear agents, friction modifiers, antioxidant and metal deactivators, viscosity index improvers, antirust agents and pour point depressants [62,64–66].

Viscous losses and lubricant shear along HL lubrication regime are demonstrated to contribute a significant amount of frictional energy losses in passenger cars and motorcycles. The viscosity of the lubricant in use predominantly influences such losses, which is proportional to the shear losses along the lubricated rubbing surfaces. Therefore, one of the easier solutions to reduce these types of frictional losses is to utilise a lower viscosity lubricant for the engine components. A drop in lubricant viscosity of 25%, corresponding to a change from SAE 40 to SAE 30 or from SAE 30 to SAE 20, is expected to correspond to engine fuel usage savings between 0.6% and 5.5% [30,51].

However, care must be taken when attempting to reduce the lubricant viscosity. This is because lesser viscous lubricants tend to have lower load bearing capacity, which could bring forward the onset of ML and BL regimes during component operation, leading to higher than expected frictional losses. Nanomaterials, such as WS<sub>2</sub>, MoS<sub>2</sub>, H<sub>3</sub>BO<sub>3</sub> and carbon nanotubes are possible lubrication additives to recover the lost load bearing capacity of the lesser viscous lubricant. With today's modern nanomanufacturing techniques, these nanomaterials have become readily available in large quantities at a relatively cheap cost. An optimised usage amount of such nanomaterials has been shown to contribute to a significant reduction in friction [67].

Most of the existing lubricant additives also consist of sulphur, chlorine and phosphorous, which could lead to poisoning of catalyst and after-treatment devices of engines. Therefore, lubricant additives, containing lesser or no-sulphated ash, phosphorous and sulphur, are heavily developed for future engines [68]. Organic lubricant additives are also being considered, especially as friction modifier additives [69]. Recent studies have shown that fatty acid based additives exhibit excellent friction modifier properties, which could delay the onset of ML and BL regimes, leading to better tribological performances [70,71].

The wrong usage or combination of some of these strategies, such as lubricant additives and surface coating pair, might increase frictional losses instead of reducing them. Tung and Gao [72,73] observed that the performance of certain lubricant additives, such as friction modifiers, along interacting surfaces vary with coating materials and their deposition methods. On top of that, Podgornik and Vizintin [74] showed that additives, like extreme-pressure (EP) additives, had no

influence on a certain type of surface coatings. This means that not necessary all types of tribological strategies can work efficiently together. Therefore, it is crucial that vehicle end-users are well educated with regards to the appropriate type of lubricants to use for every type of tribological improvements introduced by vehicle manufacturers in their respective vehicles.

## 4. Conclusions

The energy analysis conducted in this study investigates gasoline fuel energy consumed by passenger cars and motorcycles in selected Southeast Asian (SEA) countries: Indonesia, Malaysia, the Philippines, Singapore and Thailand. From the analysis, passenger cars and motorcycles in Indonesia are found to consume the most gasoline fuel, which is approximately 52.1% of the total gasoline fuel usage among the selected countries. For Malaysia, the passenger cars in use are shown to on average burn up to 8 times more gasoline fuel when compared with motorcycles in use. The fuel energy losses for these vehicle types in use in the selected SEA countries are identified by breaking down the fuel energy consumption based on exhaust and cooling losses, frictional losses and air-drag losses. It is shown that approximately 17.5% and 17.3% of the total gasoline fuel energy available are used move an average passenger car and an average motorcycle. As a result, an estimated total of USD 42.6 billion/year is wasted through fuel energy loss in moving these vehicles in the selected SEA countries, emitting as much as 109 Mtonne/year of CO<sub>2</sub>.

The proposed energy analysis framework focuses on identifying and determining the frictional energy losses while the passenger cars and motorcycles are in use in the selected SEA countries. The frictional losses for an average passenger car and an average motorcycle are estimated to be approximately 35.7% and 26%, respectively. Using the tribological improvement trends predicted by Holmberg et al. [30], the cost savings, through lesser usage of gasoline fuel as a result of frictional energy losses reduction, could amount up to USD 18.3 billion/year, with Indonesia standing to gain the most at USD 9.1 billion/year. By reducing friction, the total CO<sub>2</sub> emissions reduction that could be obtained for the selected SEA countries adds up to approximately 46.6 Mtonne/year. The CO<sub>2</sub> emissions reduction is also shown to have the most impact on Malaysia, which has the highest CO<sub>2</sub> emissions per capita among the selected SEA countries. Through implementation of relevant friction reduction strategies, the CO<sub>2</sub> emissions per capita for the transportation sector in Malaysia could possibly drop by as much as 5.8% when compared with levels in the year 2014.

The contributions from friction reduction towards greenhouse gas (GHG) emissions are also assessed with respect to the unconditional Intended Nationally Determined Contribution (INDC) as committed by the selected SEA countries during COP21. By implementing tribological improvement strategies for passenger cars and motorcycles, it is shown that the CO<sub>2</sub> emissions reduction obtained contributes around 0.8–1.9% towards the committed GHG reduction targets, individually set by the

selected SEA countries. Relevant tribological improvement strategies that could be implemented in the near future to reduce frictional losses in passenger cars and motorcycles have also been discussed. It is

emphasised that combined effort between vehicle manufacturers and end-users is required in implementing these strategies in order to avoid the inappropriate use of frictional energy reduction strategies.

### Appendix A. Conversion factors

- 1 tonne gasoline = 1000 kg.
- 1 kg gasoline = 1.342 l.
- 1 litre gasoline = 34.2 MJ.
- 1 litre gasoline = 2.35 kg CO<sub>2</sub> emissions.

### Appendix B. Specifications for average passenger car and average motorcycle

Parameters	Passenger car [30,42]	Motorcycle [42]	Unit
Engine capacity	1.7	0.109	l
Fuel consumption	0.106	0.018	l/km
Average annual mileage, $D_a$	13,000	9350 [75]	km/year
Frontal area, $A_f$	12.3	1	m <sup>2</sup>
Mass, $m$	1500	174	kg
Average vehicle speed, $v$	60	35	km/h
Average engine output, $P_{out}$	12	1.884	kW
Drag coefficient, $C_d$	0.345	0.5	–
Rolling resistance, $C_r$	0.02	0.02	–
Engine thermal efficiency, $\eta_{th}$	0.4	0.4	–
Transmission efficiency, $\eta_{tr}$	0.8	0.8	–

### Appendix C. Population and gasoline price for selected Southeast Asian (SEA) countries in 2014

Country	Population (million) [76]	Gasoline (USD/l) [76]
Indonesia	254.5	0.90
Malaysia	29.9	0.70
Philippines	99.1	1.10
Singapore	5.5	1.60
Thailand	67.7	1.30

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