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Greenhouse Gases Mitigation in the Road Transport towards 2050: Analyses of Selected Greater Mekong Sub-region (GMS) Countries

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ABSTRACT

The transport sector in the selected Greater Mekong Sub-region (GMS) countries namely, Cambodia, Lao PDR, Thailand, and Vietnam was one of the large carbon dioxide (CO_2) emission sources in 2015 of which, the road transport contributed the largest CO_2 emissions in the transport sector. The transport sector of these countries emitted 23.3% of the total CO_2 emissions in 2015. The potential of Greenhouse Gas (GHG) mitigation in the road transport is huge as vehicle technologies keep advancing. Therefore, this study presents mitigating GHG emissions from the road transport of the selected GMS countries using scenario-based analysis. Besides the Business-as-Usual (BAU) scenario, three mitigation scenarios: Alternative Fuel (AF), Modal Shift (MS), and Electric Vehicle (EV) were developed. In addition, each countermeasure scenario is divided into two levels namely, low-ambition and high-ambition levels of GHG mitigation. The Low Emissions Analysis Platform (LEAP) model is used to estimate the energy demand and GHG emissions. The findings of the study show that the total GHG emissions in the road transport of the selected GMS countries in 2050 will be reduced by 69.75% in the high EV (EVH) scenario, 26.15% in the high AF (AFH) scenario, and 52.24% in the high MS (MSH) scenario. Results reveal that EVs have a high potential to mitigate GHG emissions in the road transport. Therefore, policymakers should encourage people to shift from conventional vehicles to EVs. In addition, the government should strive to attract EV manufacturers and provide incentives to those firms as well as EV owners. Furthermore, the electricity supply for EVs should come from green energy.

1. INTRODUCTION

Climate change, mainly caused by greenhouse gas (GHG) concentrations in the atmosphere such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), has become a tackling concern for the world since the last few decades. It is known to have long-term disastrous effects [1]. The transport sector is one of the main sectors contributing to global climate change. As the global energy demand in the transport sector kept increasing rapidly, the transport sector became the second largest CO_2 emitter [2]. The global CO_2 emissions in the transport sector were accounted for approximately 23.8% in 2015 [2]. The combustion of fossil fuels in the transport sector caused global CO_2 emissions to grow by about 1.7 times during 1990-2015 [2]. Similarly, the transport sector within the selected Greater Mekong Sub-region (GMS) countries is emerging along with their remarkable economic growth. The energy demand in the transport sector in Cambodia increased by around 2.9 times during 2005-2015, whereas in Lao PDR, Thailand, and Vietnam, the energy demand increased by approximately 2.3 times, 1.3 times, and 1.7 times, respectively [2].

The transport sector of the selected GMS countries depends heavily on the road transport. In Cambodia, road transport was estimated to have a modal share of about 90% of the transport sector [3]. The estimated passenger-kilometer (pkm) covered more than 82% of the road transport in Cambodia in 2015, whereas the rest was generated by the freight ton-kilometer (tkm) [4], [5]. The total number of vehicles in Cambodia in 2015 was approximately 3.59 million of which, motorcycles and sedans accounted for 81% and 11%, respectively [5]. There are only two types of fuel used in the road transport of Cambodia: gasoline and diesel. Similarly, as a landlocked country, Lao PDR's road transport is the backbone of the country's transport sector. In 2015, the road transport covered more than three-quarters of the passenger travel demand and 83% of the freight traffic (ton-kilometer) [6], [7]. The total number of vehicles in Lao PDR 2015 was about 1.67 million, mainly are motorcycles and sedans [8]. The main energy sources for the road transport in the country are gasoline and diesel.

Thailand had the most travel demand among the four countries in 2015. The road transport of Thailand was accounted for approximately 88% and 91% of the

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total passenger-kilometer and ton-kilometer, respectively, in 2015 [9]. The total number of vehicles in Thailand in 2015 was reported to be around 36.46 million. Shares of motorcycles and sedans were 56.2% and 21.2% in the total number of vehicles, respectively [10]. Unlike, Cambodia and Lao PDR, Thailand utilizes various types of fuels in the road transport such as gasoline, diesel, biodiesel, ethanol, electricity, compressed natural gas (CNG), liquefied petroleum gas (LPG), and fuel oil. The transport sector in Vietnam does not solely rely strongly on road transport, however, road transport still plays a vital role in the transport sector. In 2015, the passenger demand in the road transport covered about 68.1% of the total passenger-kilometer in Vietnam. In contrast, the freight traffic demand by road in Vietnam in 2015 was responsible for only 22.4% of the total ton-kilometer [11]. The main freight traffic demand in Vietnam in 2015 was the maritime transport. The number of vehicles in Vietnam in 2015 was approximately 47.11 million of which, motorcycles covered nearly 94% of the total number of vehicles [12]. The only two types of fuels used in the road transport of Vietnam are gasoline and diesel.

Based on the background information, the potential to mitigate GHG emissions from the road transport in the selected GMS countries is considerably high as the road transport relies heavily on the use of diesel and gasoline. Furthermore, the advanced technology like battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), and hybrid electric vehicles (HEVs) would contribute to higher GHG mitigation opportunity in the road transport. Thus, this study seeks to propose cost-effective mitigation alternatives for supporting low-carbon development strategies in the selected GMS countries towards 2050. Three scenarios besides the BAU scenario are developed. The three countermeasure scenarios are Alternative Fuel (AF), Modal Shift (MS), and Electric Vehicle (EV). Each of the three counter scenarios is divided into two levels namely, low-ambition and high-ambition levels of GHG mitigation. The Low Emissions Analysis Platform (LEAP) model which was developed by the Stockholm Environment Institute (SEI), is used to assist in the estimation of energy demand and GHG emissions in the road transport of the selected GMS countries.

2. OVERVIEW OF THE ROAD TRANSPORT IN SELECTED GREATER MEKONG SUB-REGION COUNTRIES

2.1 Energy Demand

During 2010-2015 as the economy potentially grew, the total energy demand in the road transport of the selected GMS countries saw an annual average growth rate (AAGR) of 2.9%, of which AAGRs of the energy demand in the road transport of Cambodia, Lao PDR, Thailand, and Vietnam were recorded to be 12.5%, 15.1%, 3.1%, and 1.2%, respectively [13]-[17]. The demand for diesel and gasoline in the road transport in the selected GMS countries had increased with AAGRs of 0.4% and -3.4%, respectively, during 2010-2015 [13]-[17].

In 2015, the demand for diesel and gasoline in the road transport in Cambodia covered 57% and 43%, respectively, whereas the shares in Lao PDR were 80% and 20%, respectively [13],[14]. Unlike Cambodia and Lao PDR, the demand for diesel and gasoline in Thailand in 2015 collectively was accounted for only 49% of the total energy demand in the road transport. The rest of the energy demand belonged to LPG (9%), gasohol (30%), natural gas (12%), and other petroleum products [16]. In Vietnam, diesel and gasoline had the shares of 52% and 48% among the total energy demand in the road transport in 2015, respectively [17].

2.2 CO_2 Emissions

In 2015, the average CO_2 emission factor (EF) in the power sector in the selected GMS countries was 0.47 kg/kWh [2],[18]. Cambodia had the highest CO_2 EF at 0.68 kg/kWh and followed by Thailand, Vietnam, and Lao PDR which had CO_2 EFs of 0.52 kg/kWh, 0.43 kg/kWh, and 0.25 kg/kWh, respectively [2],[18].

2.3 Marginal Abatement Cost

The cost of reduction per unit of emission is measured by the Marginal Abatement Cost (MAC). Moreover, the Marginal Abatement Cost Curve (MACC) classifies best-to-worst mitigation methods. The technological classification offered by the MACC assists policymakers, government, and organizations to decide the best way to reduce emissions by selecting technologies. The MACC shows the best choice with the lowest MAC value, while the worst choice has the highest MAC value. The MAC value can be either positive or negative. If the low-carbon option has a negative MAC value, then it shows that the alternative is less expensive than the baseline option, whereas the positive MAC value shows the opposite. Normally, low-carbon technology is likely to be expensive when compared to traditional technology. This is not always the case, though. The MAC not only covers the equipment's capital cost, but also the costs of O&M and the fuel. The MAC value is likely to be negative if fuel cost savings are more than the incremental capital cost of the new equipment.

3. BIOFUELS AND ELECTRIC VEHICLES

3.1 Biofuels

Biofuels can be used as alternative fuels to the petroleum utilized in the transport sector. Different types of biofuels such as B5 (5% biodiesel blend with 95% petroleum diesel), B20 (20% biodiesel blend with 80% petroleum diesel), B100 (100% biodiesel), E5 (5% ethanol blend with 95% gasoline), E10 (10% ethanol blend with 90% gasoline), E15 (15% ethanol blend with 85% gasoline), E85 (85% ethanol blend with 15% gasoline), E100 (100% ethanol) are currently being used in the transport sector across the world. Global biofuel production increased from 99 billion liters in 2010 to 126 billion liters in 2015. Biofuel output was expected to increase to 500 billion liters by 2030 in the Sustainable Development Scenario of the International

Energy Agency (IEA) [19]. Among the selected GMS countries, Thailand is the largest biofuel producer and consumer.

The fuel economy of vehicles using biofuels is likely to be lower than that of vehicles using petroleum. Tuan and Tuan [20] investigated the impacts of E5 and E10 fuels on the performance and exhaust emissions of motorcycle and car in Vietnam. The results suggested that there were reductions in the emissions such as CO and HC [20]. Eight heavy-duty vehicles such as transit buses, school buses, freightliner trucks, and motorcoach were tested [21]. The vehicles were tested on the diesel-fueled and B20-fueled and the outcomes suggested that on average there were 16%, 17%, and 12% reductions in PM, CO, and HC when B20 fuel was used instead of diesel. The NO_x emissions impact of the B20 did not change, statistically [21]. Varieties of fuels for passenger cars in Vietnam such as Research Octane Number 92 (RON92) gasoline, E10 gasoline, E15 gasoline, and E20 gasoline were tested. The findings of the experiment showed that for the carbureted car, there were reductions in fuel consumption, CO, and HC emissions, while the NO_x emissions saw an increment when compared to RON92 gasoline. However, for fuel-injected cars, the blends did not affect fuel consumption and increments in HC and CO emissions were seen for all alternative fuels tested [22].

3.2 Electric Vehicles

Electric vehicles (EVs) are the vehicles operated by electric energy. As a car, the EV is silent, easy to drive, and has no fuel costs like standard vehicles. It is very useful as a means of urban transportation. It does not emit while idling. It is capable of regular start-stop operation. It delivers the entire torque from start-up and has no trips at the gas station nor does it add to the smog that pollutes the city's climate [23]. EVs have 2 to 3 times better fuel economy than internal combustion engine vehicles, which contributes to lower renewable energy consumption compared with biofuels [24]. The global electric car stock in 2015 hit a record of 1.26 million (all electric vehicles including plug-in hybrid electric vehicles) [25]. A target of 100 million electric cars and 400 million 2-wheelers and 3-wheelers were set to be reached in 2030 according to the Paris Declaration on Electro-Mobility and Climate Change and Call to Action [25].

A study on electric vehicles (including hybrid and plug-in hybrid vehicles) in Thailand was done in 2014 to observe CO_2 emissions in road transport. Different rates of penetration of electric vehicles were considered and the results of the study suggested that electric vehicles could be able to reduce 689 ktoe of energy demand for transport by 2030. Also, the CO_2 emissions reduction of 4.84 Mt-CO_2eq could be achieved in 2030 [26]. However, CO_2 emissions from the electricity supply were not included [26]. When the shares of electric cars (including PHEVs, HEVs, and BEVs) and electric motorbikes reach 34% and 30% of the total number of cars and motorbikes, respectively, in Vietnam’s road transport in 2040, the overall CO_2 emissions in Vietnam will be increased by 5.2% annually due to strong reliance on fossil-fuel to generate electricity [27]. A greater understanding of how the combination of the electrical sector and land transportation would affect land transportation. GHG emissions will necessitate a potential examination of the national grid emission factor [28]. If the electricity generation industry is not decarbonized, the impact of BEV penetration will be restricted in reducing CO_2 emissions.

4. METHODOLOGY

The overview of the methodology for this study is shown in Figure 1. Different scenarios have to be accomplished in order to get to the results, where GHG mitigation potential in the road transport within the selected GMS countries is discussed.

4.1 Low Emissions Analysis Platform (LEAP)

The Low Emissions Analysis Platform (LEAP) applies both the top-down and bottom-up modeling methods to assess energy policy and climate change mitigation [29]. The LEAP has been applied in different studies to estimate energy production, emission inventories, and environmental costs, using different user-specified scenarios. The LEAP model has been used to analyze the long-term energy supply and demand, and GHG reduction targets in several Asian countries [26],[29]-[32].

4.1.1 Calculation Mechanism of LEAP Model

The calculations of energy consumption, transformation system, and carbon emissions of the LEAP model are shown in the following equations.

1) Energy Consumption

The total final energy consumption is calculated as follows [32]:

$$EC_n = \sum_i \sum_j AL_{n,j,i} \cdot EI_{n,j,i} \tag{1}$$

where *EC* is the aggregate energy consumption of a given sector (Mtoe or TWh), *AL* is the activity level, *EI* is the energy intensity (Mtoe or TWh), *n* is the fuel type, *i* is the sector, and *j* is the device.

The net energy consumption for transformation is defined as [32]:

$$ET_s = \sum_m \sum_t ETP_{t,m} \cdot \left(\frac{1}{f_{t,m,s}} - 1\right) \tag{2}$$

where *ET* is the net energy consumption for transformation (Mtoe or TWh), *ETP* is the energy transformation product (Mtoe or MJ), *f* is the energy transformation efficiency (%), *s* is the type of primary energy, *m* is the equipment, and *t* is the type of secondary energy.

2) Transformation

The transformation section converts the primary energy to secondary energy and also consists of the conversion of electricity transmission and distribution centers. The transformation section includes power plants, petroleum refineries, coal mining, and so on [32]:

For each process p:

$$INPUT_p = \frac{OUTPUT_p}{EFFICIENCY_p} \tag{3}$$

where $INPUT$ is the fuel or feedstock (MJ or Mtoe), $OUTPUT$ is the electricity generated or the refinery/production output (TWh or Mtoe or MJ), $EFFICIENCY$ is the efficiency of the power plants or refinery plants (%).

For a transmission and distribution module:

$$EFFICIENCY_p = 1 - LOSSES_p \tag{4}$$

3) Carbon Emission

The carbon emission from final energy consumption is calculated as follows [32]:

$$CEC = \sum_i \sum_j \sum_n AL_{n,j,i} \cdot EI_{n,j,i} \cdot EF_{n,j,i} \tag{5}$$

where CEC is the carbon emission (tonne or million tonne), AL is the activity level, EI is the energy intensity (TWh or Mtoe), EF is the carbon emission factor from fuel type n for equipment j from sector i.

The carbon emission from energy transformation is calculated as follows [32]:

$$CET = \sum_s \sum_m \sum_t ETP_{t,m} \cdot \frac{1}{f_{t,m,s}} \cdot EF_{t,m,s} \tag{6}$$

where CET is the carbon emission (Tonne or Million Tonne), ETP is the energy transformation product (Mtoe or MJ), f is the energy transformation efficiency (%), EF is the emission factor from one unit of primary fuel consumed for producing secondary fuel type t through equipment m.

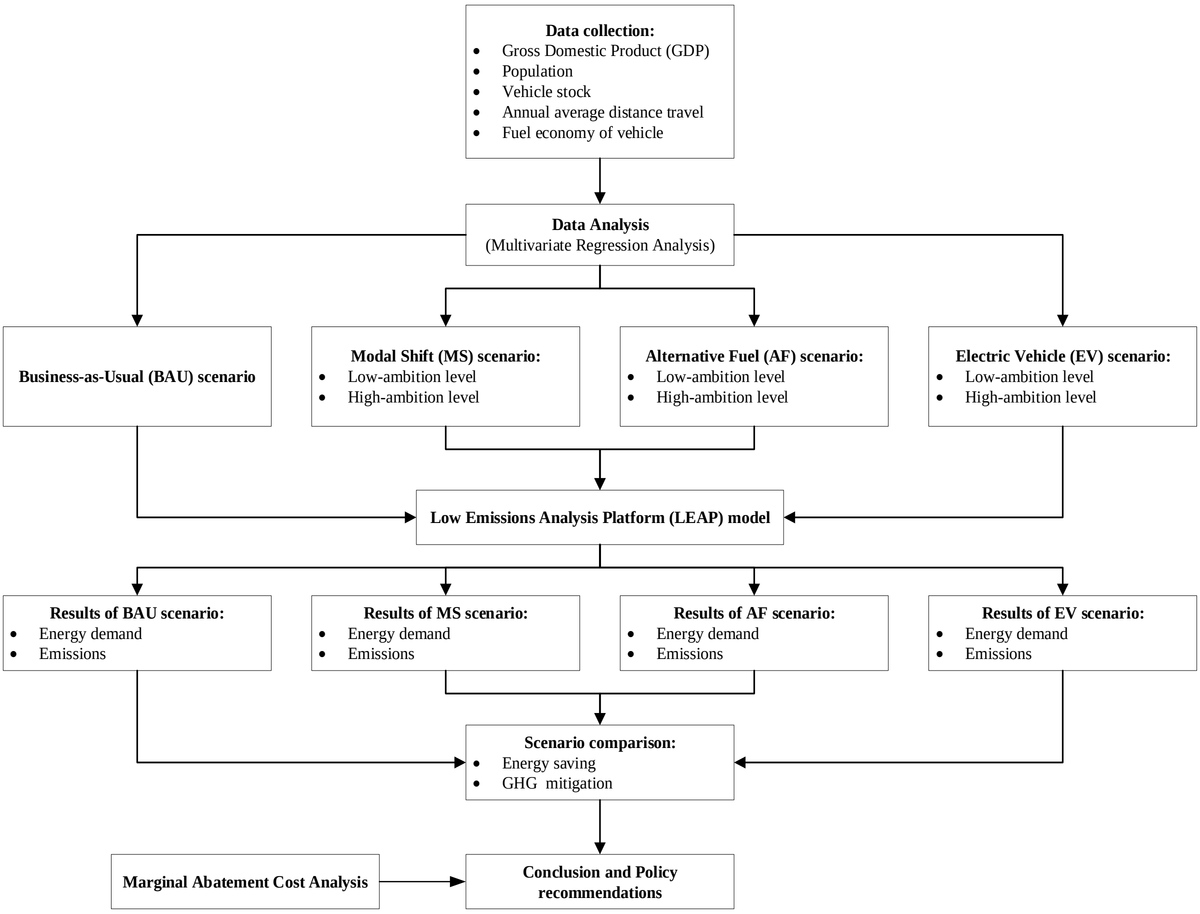

Fig. 1. Flowchart of the methodology.

4.1.2 Structure of the Demand Module in LEAP Model

In this study, the road transport is divided into two categories namely, passenger transport and freight transport. Within the selected GMS countries, as a whole, the vehicles in the passenger transport are categorized into seven types: sedans, motorcycles, tuk-tuks, vans, taxis, SUVs, and buses. On the other hand, there are only two types of vehicles in the freight transport of this study. The two vehicle types in freight transport are light duty vehicles or pick-ups and trucks. Nonetheless, each of the four countries has its specific vehicle type structure and does not necessarily consist of all the vehicle types in the selected GMS countries as a whole as can be seen from Figure 2, Figure 3, Figure 4, and Figure 5. The modelling for four countries are different from each other, *i.e.*, one model is created for one country.

The fuel types used in the road transport sub-sector in each of the selected GMS countries are conventional gasoline, conventional diesel, compressed natural gas (CNG), liquefied petroleum gas (LPG), gasohol (E10, E20, E85), biodiesel (B20), bioethanol (ED95), and electricity. The fuels that are the blend of gasoline and 10% of ethanol, 20% of ethanol, and 85% of ethanol are called E10, E20, and E85, respectively. The fuel that is the blend of diesel and 20% of biodiesel is called B20. ED95 fuel is a high blend of 96.5% hydrous bioethanol and 3.5% additives.

4.2 Data and Assumptions

The energy demand estimation in the road transport in the selected GMS countries can be done through the use of key parameters such as the number of vehicles, vehicle kilometer travel, and fuel economy of the vehicle.

$$ED_{i,j} = NV_{i,j} \times VKT_i \times FE_{i,j} \tag{7}$$

where *i* is the vehicle type, *j* is the fuel type, *ED* is the energy demand of the vehicle (Mtoe or kWh), *NV* is the number of vehicles, *VKT* is the vehicle kilometer of travel, and *FE* is the fuel economy of the vehicle (liter/km or kWh/km).

The *VKT* is the annual average driving distance of a specific type of vehicle. The *VKT* of each of the selected GMS countries is selected from different sources and assumptions. The *VKT* in each of the selected GMS countries is different from each other [4], [33]-[35]. The fuel economy of the vehicle is taken from reports and databases along with the experts' opinions and assumptions [33], [34], [36], [37]. The VKT of one country is used to estimate the energy demand of that country. However, the average *VKT* and the fuel economy of the vehicle of the selected GMS countries as a whole are shown in Table 1.

The future number of vehicles is estimated through the multivariate regression analysis having the population and Gross Domestic Product (GDP) per Capita and Population as independent parameters because both of the freight and passenger demands are driven predominantly by GDP. The historical data of population and GDP per capita from 2005 to 2015 is collected to conduct the regression analysis. The estimated future number of vehicles will keep increasing to reach a saturation level following an S-curve function. Thus, to make the regression analysis more realistic, a saturation level of 600 vehicles per 1000 habitants is chosen for Thailand and Vietnam, while a saturation level of 500 vehicles per 1000 habitants is assumed for Cambodia and Lao PDR [38].

$$log\left(\frac{NV_{1000}}{SL\text{-}NV_{1000}}\right) = \alpha + \beta \times log\left(GDP_{per\ capita}\right) + \lambda \times log\left(POP_{1000}\right) \tag{8}$$

where NV_{1000} is the number of vehicles per 1000 habitants, *SL* is the saturation level of "vehicles per 1000 habitants", POP_{1000} is the population in terms of thousands, α, β, and λ are the coefficients.

The timeline in this study is from 2015 until 2050. The historical number of vehicles by type is collected from various reports and relevant governmental data [5], [8], [10], [12]. The GDP and population from 2005 to 2015 of Cambodia, Lao PDR, and Vietnam are collected from the World Bank database [39], [40]. On the other hand, the GDP from 2005 to 2015 of Thailand is collected from the Office of the National Economic and Social Development Board (NESDB) [41]. The GDPs of Cambodia, Lao PDR, Thailand, and Vietnam during 2016-2050 are assumed to grow at AAGRs of 6.2%, 4.9%, 2.9%, and 5%, respectively [42]-[44]. However, the GDP growth rates of each country will not stay constant at the above given rates. The future growth rates will slowly decrease. The population from 2016-2050 of Cambodia, Lao PDR, Thailand, and Vietnam would have AAGRs of 1%, 1%, -0.1%, and 0.5%, respectively [45].

Table 1. Average Vehicle Kilometer Travel (VKT) and Fuel Economy (FE) by vehicle types in the selected GMS countries.

Vehicle Type	VKT (km/year)	FE (km/liter)
Motorcycle	9,039	34.13
Tuk-Tuk	16,924	12.13
Sedan	19,300	11.46
SUV	9,100	11.97
Van	31,204	8.33
Taxi	22,700	11.78
Bus	45,094	3.27
Pick-Up	27,218	10.44
Truck	27,197	4.35

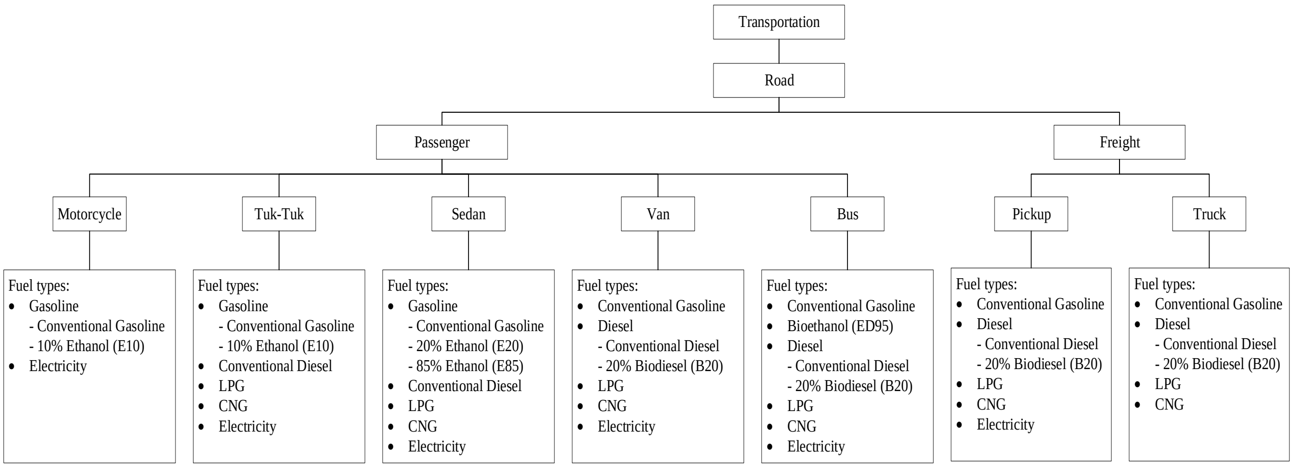

Fig. 2. Structure of Cambodia's road transport in the LEAP model.

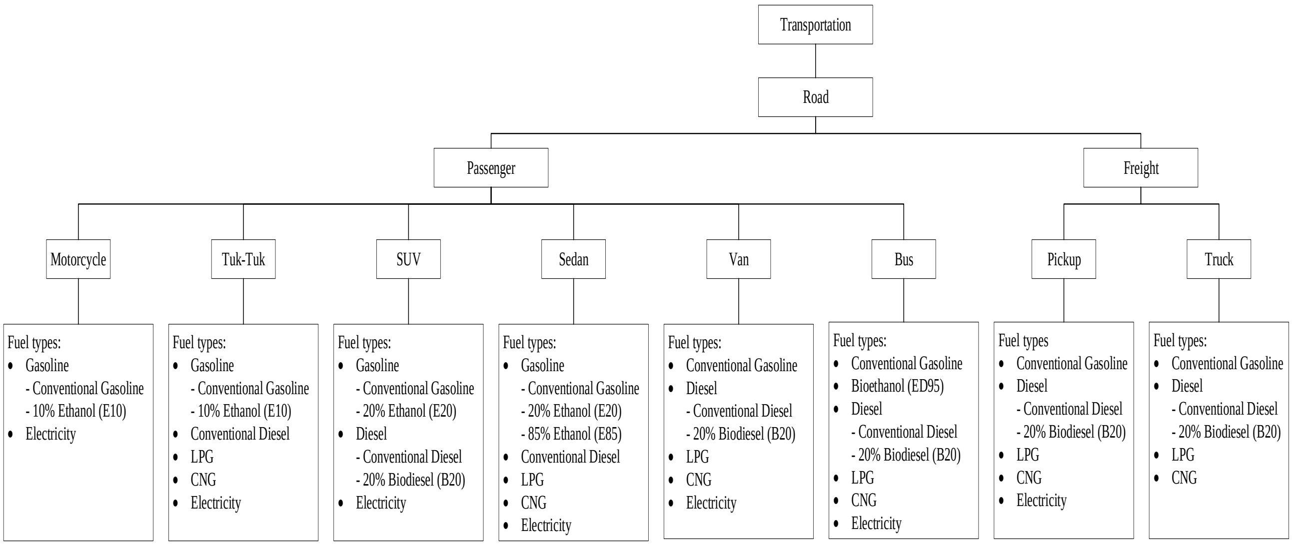

Fig. 3. Structure of Lao PDR's road transport in the LEAP model.

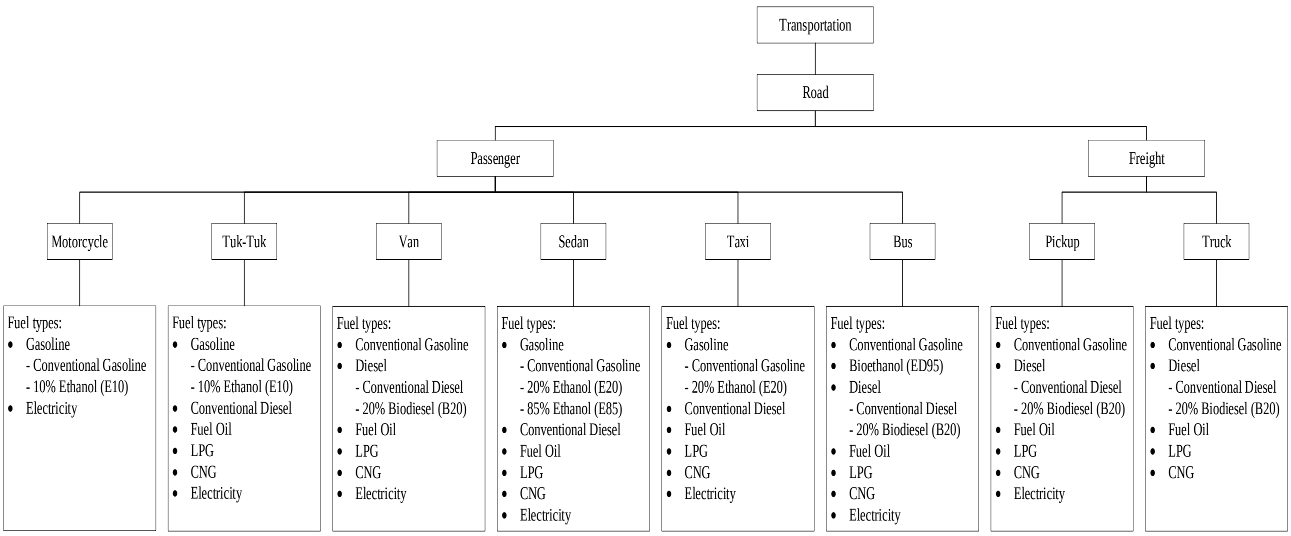

Fig. 4. Structure of Thailand's road transport in the LEAP model.

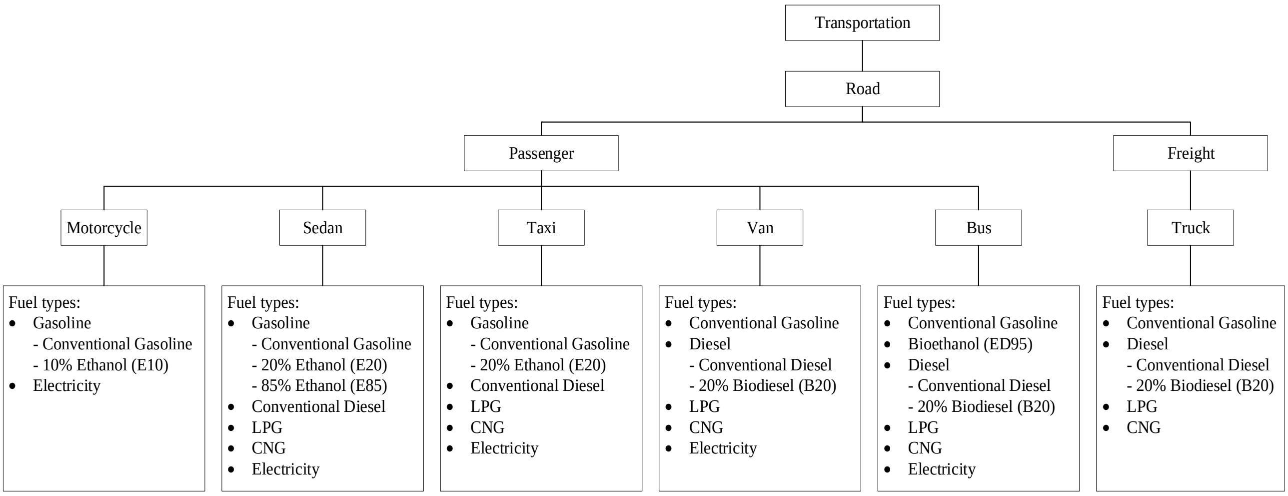

Fig. 5. Structure of Vietnam's road transport in the LEAP Model.

4.3 Scenario Development

This study consists of the analysis of four main scenarios namely, Business-as-Usual (BAU), Alternative Fuel (AF), Modal Shift (MS), and Electric Vehicle (EV). Moreover, each counter scenario is divided into two levels: low-ambition and high-ambition levels of GHG mitigation. The BAU scenario is the reference case of road transport in the selected GMS countries. The future trend of the transportation modes, vehicle technologies, and fuel types of this scenario is the same as in the base year which is 2015. The AF, MS, and EV scenarios are analyzed to investigate the impacts of cleaner fuels, public transportation modes, and electric vehicles on the energy demand and GHG emissions in the road transport sub-sector. The GHG emissions that are considered in this study are only Carbon Dioxide (CO_2), Methane (CH_4), and Nitrous Oxide (N_2O).

4.3.1 Business-as-Usual (BAU) Scenario

In the BAU scenario, shares of transportation modes, fuel types used in the sub-sector, and vehicle technologies in the base year are assumed to remain unchanged throughout the study period. This static analysis will not necessarily reflect the dynamic character of reality. The scenario analyses are indicative. The future number of vehicles is estimated through the regression analysis using historical population and GDP per capita from 2005 to 2015 and are shown in Table 2, Table 3, Table 4, and Table 5.

Table 2. Number of vehicles by vehicle types in Cambodia.

Vehicle Type	2015	2030	2050
Motorcycle	2,905,216	6,801,933	8,730,582
Tuk-Tuk	59,290	138,815	178,175
Sedan	392,262	918,396	1,178,802
Van	54,130	126,732	162,667
Bus	7,369	17,253	22,145
Pick-Up	100,075	234,303	300,738
Truck	72,196	169,031	216,959

Table 3. Number of vehicles by vehicle types in Lao PDR.

Vehicle Type	2015	2030	2050
Motorcycle	1,280,673	2,909,158	3,546,461
Tuk-Tuk	8,761	19,901	24,261
Sedan	51,540	117,077	142,725
SUV	24,665	56,029	68,303
Van	46,293	105,158	128,195
Bus	4,448	10,104	12,317
Pick-Up	204,360	464,221	565,917
Truck	46,654	105,979	129,195

Table 4. Number of vehicles by vehicle types in Thailand.

Vehicle Type	2015	2030	2050
Motorcycle	20,499,211	23,005,019	24,139,786
Tuk-Tuk	20,287	22,767	23,890
Sedan	7,742,434	8,688,860	9,117,460
Taxi	114,794	128,826	135,181
Van	547,662	614,608	644,925
Bus	153,757	172,552	181,064
Pick-Up	6,135,571	6,885,578	7,225,223
Truck	1,517.301	1,702,770	1,786,770

Table 5. Number of vehicles by vehicle types in Vietnam.

Vehicle Type	2015	2030	2050
Motorcycle	44,128,822	57,801,784	61,588,500
Sedan	874,943	1,146,037	1,221,116
Taxi	96,505	126,406	134,687
Van	1,033,13	1,353,240	1,441,890
Bus	118,030	154,601	164,729
Truck	853,735	1,118,260	1,191,520

4.3.2 Alternative Fuel (AF) Scenario

The AF scenario substitutes conventional fuels with cleaner fuels such as CNG, LPG, gasohol (E10, E20, and E85), biodiesel (B20), and bioethanol (ED95). The fuel substitution is applied to all types of vehicles, *i.e.*, motorcycles, tuk-tuks, sedans, SUVs, taxis, vans, buses, pick-ups, and trucks. The AF scenario is classified into two levels which are low-ambition AF (AFL) and high-ambition AF (AFH). Each level in the AF scenario consists of different indicative rates of clean fuel substitution over conventional fuels as can be found in Table 6.

Table 6. Measures in the Alternative Fuel scenario in 2050.

Country	Fuel switching to cleaner fuels		
	BAU 2050	AFL 2050	AFH 2050
Cambodia	0%	35%	60%
Lao PDR	0%	35%	60%
Thailand	0%	50%	80%
Vietnam	0%	35%	60%

4.3.3 Modal Shift (MS) Scenario

The MS scenario assumes that the future transportation modes will partly shift from private transportation modes to public transportation modes, *i.e.*, buses and rail transport. The MS scenario is divided into two levels: low-ambition MS (MSL) and high-ambition MS (MSH). The modal shifts from private transportation modes such as sedans, motorcycles, SUVs, vans, tuk-tuks, and taxis to public transportation are applied to each of the selected GMS countries at different rates. The private transportation modes contribute to the increasing energy demand in the road transport and the land traffic congestion. Thus, this study assumes different indicative rates of vehicle modal shifts as shown in Table 7 to observe the impact of public transportation on the energy demand and GHG emissions in road transport of the selected GMS countries. Nonetheless, it should be noted that the shifts from private modes happen differently in each private mode. Moreover, the energy demand of the rail transport will not be included in the paper.

4.3.4 Electric Vehicle (EV) Scenario

The EV scenario proposes to substitute the existing vehicle technologies with electric-powered vehicles namely, Battery Electric Vehicles (BEVs), Plug-in Hybrid Electric Vehicles (PHEVs), and Hybrid Electric Vehicles (HEVs). In this study, the motorcycles, tuk-tuks, sedans, and taxis are grouped as BEVs. The SUVs, sedans, and taxis are grouped as PHEVs. Lastly, the sedans, taxis, and vans are grouped as HEVs. The EV scenario is categorized into two levels namely, low-ambition EV (EVL) and high-ambition EV (EVH). Electric vehicles consume electricity which means that the GHG emissions of the electric vehicles do not directly come from the vehicles, but from the power sector which produces electricity. Table 8 presents the indicative measures in the EV scenarios in the selected GMS countries in 2050.

Table 7. Measures in the Modal Shift scenario in 2050.

Country	BAU 2050	MSL 2050	MSH 2050
Cambodia			
- Shift to Bus	9.6%	30%	35%
- Shift to Rail Transport	0%	35%	40%
Lao PDR			
- Shift to Bus	21%	30%	35%
- Shift to Rail Transport	0%	35%	40%
Thailand			
- Shift to Bus	32%	35%	40%
- Shift to Rail Transport	0%	40%	50%
Vietnam			
- Shift to Bus	23%	35%	40%
- Shift to Rail Transport	0%	40%	50%

Table 8. Measures in the Electric Vehicle scenario in 2050.

Country	Shares of Electric Vehicles (BEVs, PHEVs, HEVs)		
	BAU 2050	EVL 2050	EVH 2050
Cambodia	0%	60%	100%
Lao PDR	0%	60%	100%
Thailand	0%	75%	100%
Vietnam	0%	75%	100%

4.4 Marginal Abatement Cost

In this study, GHG abatement cost takes into consideration the capital cost, O&M cost, and fuel cost, and the subsidies on biofuel. For the MAC analysis, only the GHG emissions are considered and only apply to only some of the measures in the AFH and EVH scenarios.

The MAC analysis in road transport in the selected GMS countries can be calculated using Equation 9 [46].

$$MAC = \frac{GHG\ Abatement\ Cost\ (USD)}{Reduction\ of\ GHG\ (t\text{-}CO2eq)} \tag{9}$$

5. RESULTS

This section presents the results of the modeling in terms of energy demand and GHG emissions in the road transport sub-sector in the selected GMS countries.

5.1 Energy Demand

The energy demand in the road transport sub-sector in the selected GMS countries would increase from 48.58 Mtoe in 2015 to 69.64 Mtoe in the BAU scenario in 2050. It shows an AAGR of 1.24% during the study period. About 56.96% of the energy demand in the BAU scenario in 2050 would belong to passenger transport, while the rest would belong to freight transport.

Individually, Cambodia, Lao PDR, Thailand, and Vietnam would share 21.47%, 4.3%, 47.26%, and 26.97% of the total energy demand in road transport in the selected GMS countries, respectively, in the BAU scenario in 2050.

The fuel switching from conventional fuels to clean fuels in the road transport in the AFL and AFH scenarios would result in an energy reduction of 12.89% and 14.6%, respectively, from the BAU scenario in 2050. Thailand would have the most energy reductions in the AFL and AFH scenarios. Vietnam would have the second most energy reduction in the AFL scenario, but Cambodia would claim the standing in the AFH scenario. I Similarly, the modal shifts from private transportation modes to public transportation at different levels such as the MSL and MSH scenarios show satisfying energy reduction rates of 41.84% and 52.54%, respectively, when compared to the BAU scenario in 2050. Thailand will be the country achieving the most energy reduction in the MSL and MSH scenarios and followed by Vietnam, Cambodia, and Lao PDR, respectively. In the EVL and EVH scenarios, the energy demand in the road transport in the selected GMS countries will be reduced by 45.28% and 63.65%, respectively, from the BAU scenario in 2050 as shown in Figure 6.

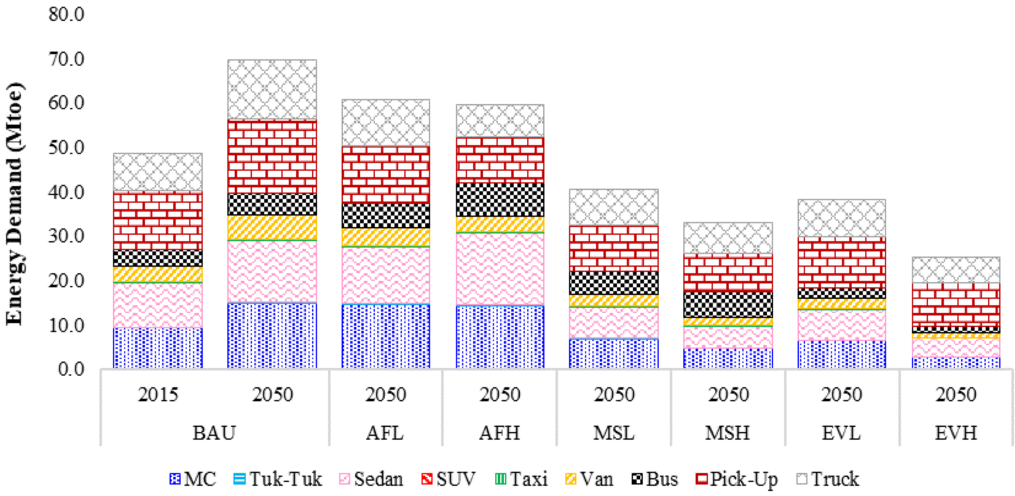

Fig. 6. Total energy demand in the road transport in the selected GMS countries.

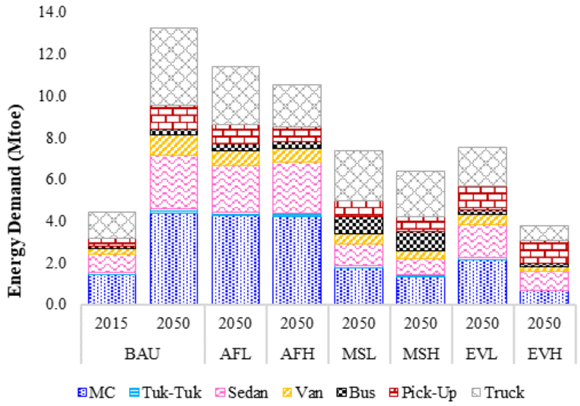

Fig. 7. Energy demand by vehicle types in Cambodia.

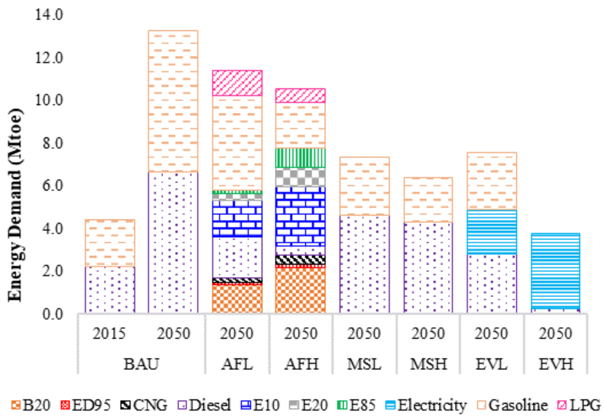

Fig. 8. Energy demand by fuel types in Cambodia

5.1.1 Cambodia

The energy demand in road transport in Cambodia will increase from 4.4 Mtoe in 2015 to 13.24 Mtoe in 2050 under the BAU scenario. The demand for diesel and gasoline would be 50.2% and 49.8% of the total energy demand in road transport in Cambodia in 2050 as can be seen in Figure 7 and Figure 8.

Even though the number of motorcycles in Cambodia in 2050 accounts for more than three-quarters of the total number of vehicles, the motorcycles would only be responsible for 32.98% of the total energy demand in the road transport sub-sector in the BAU scenario in 2050. Sedans, pick-ups, and trucks would be responsible for 19.51%, 8.92%, and 27.69% of the total energy demand in road transport in Cambodia in 2050, respectively. Figure 8 illustrates the energy demand by types of fuel in the road transport in Cambodia.

The energy demand in the road transport in Cambodia in 2050 will be reduced by 13.8% in the AFL scenario, whereas the reduction in the EVH scenario will be 20.5%. In the AFH scenario, the demand for E10 fuel would account for 26.16% of the total energy demand in road transport, while the shares of gasoline, diesel, B20 will be 20.36%, 4.26%, and 20.65%, respectively in 2050.

5.1.2 Lao PDR

The total energy demand in the road transport in Lao PDR will increase from that in 2015 by 2.77 times in 2050 in the BAU scenario. Lao PDR would see reductions of the energy demand of 30.42%, 47.09%, and 66.12% in the AFH, MSH, and EVH scenarios, respectively. In the BAU scenario in 2050, trucks will take up the majority of the total energy demand in the road transport in Lao PDR which would account for 36.74%. Tuk-Tuks will have the least share among the total energy demand in 2050 in Lao PDR accounting for 1.04%, while the shares for pick-ups and motorcycles would be 16.83% and 18.68%, respectively. As a result of using electric vehicles, in the EVH scenario, the energy demand of motorcycles in 2050 will have a share of only 8.09%, whereas trucks will have a share of 38.08% as shown in Figure 9.

Figure 10 represents the energy demand by types of fuel in the road transport in Lao PDR

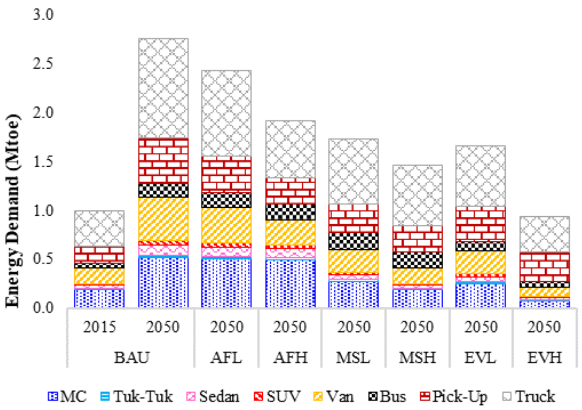

Fig. 9. Energy demand by vehicle types in Lao PDR.

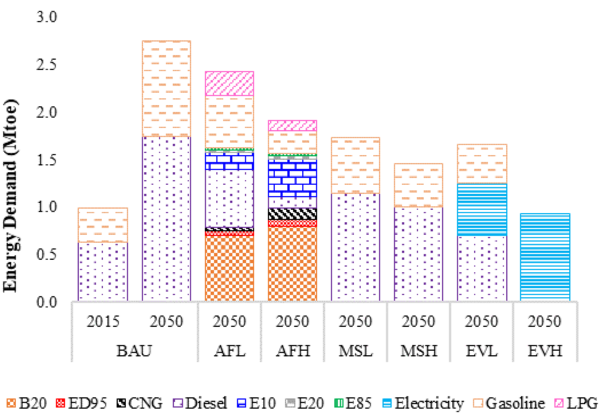

Fig. 10. Energy demand by fuel types in Lao PDR.

Similar to Cambodia, the demand for diesel and gasoline in the BAU scenario in Lao PDR would share 63.3% and 36.7%, respectively, of the total energy demand in road transport in 2050. With the presence of alternative fuels, the diesel and gasoline demand in the road transport in Lao PDR would be reduced to only 6.07% and 12.32%, respectively, in the AFH scenario in 2050. Other than that, the shares of B20, E10, E20, and E85 fuels will be 41.49%, 20.33%, 2.11%, and 1.44%, respectively, in the same scenario.

5.1.3 Thailand

Thailand's energy demand in the road transport in the BAU scenario in 2050 will increase from that in 2015 by 15.08%, indicating an AAGR of 0.43% during the study period as can be seen in Figure 11.

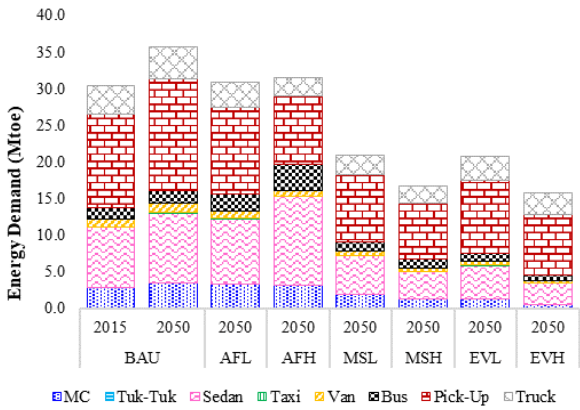

Fig. 11. Energy demand by vehicle types in Thailand.

The energy demand in the road transport in Thailand is more diversified than in the other three countries. In Thailand, pick-ups, sedans, trucks, and motorcycles are the four most energy consumers in the road transport by 2050 in the BAU scenario. The demand for these four types of vehicles will be largely reduced in the EVL and EVH scenarios by 2050. In the MSH scenario, the energy demand for the four vehicle types in 2050 will be collectively reduced by 17.87 Mtoe from the BAU scenario. In addition, Figure 12 presents the energy demand by fuel types in Thailand.

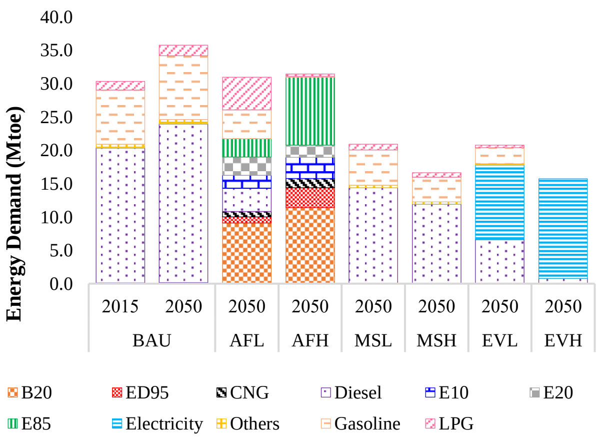

Fig. 12. Energy demand by fuel types in Thailand.

In the BAU scenario in 2050, the demand for CNG, LPG, diesel, and gasoline would be accounted for 0.4%, 4.43%, 66.6%, and 26.74% of the total energy demand in road transport, respectively. The demand for diesel will drop to 0% in the AFH scenario, however, the demand for B20 fuel will surge up to 36.31% in the same scenario. When all of the vehicles are assumed to be entirely or partly run on electricity, the demand for electricity in the EVH scenario will be accounted for only 94.96% of the total demand in that scenario.

5.1.4 Vietnam

By 2050, the energy demand in the road transport in Vietnam will increase from 12.8 Mtoe in 2015 to 17.9 Mtoe, showing an AAGR of 1.13% during 2015-2050. The majority of the demand will be covered by motorcycles which will be accounted for more than 35% of the energy demand in this particular sub-sector as can be seen from Figure 13. The buses and vans will have the same share of 15%, in the energy demand in 2050 in the BAU scenario. As a result of the transport modal shift, the energy demand for buses will increase from the BAU scenario by 1.25 times in the MSH scenario, while the demand for motorcycles, sedans, and vans will be reduced by 71.94%, 71.94%, and 71.94%, respectively, in the same scenario. Figure 14 illustrates the energy demand by fuel types in Vietnam.

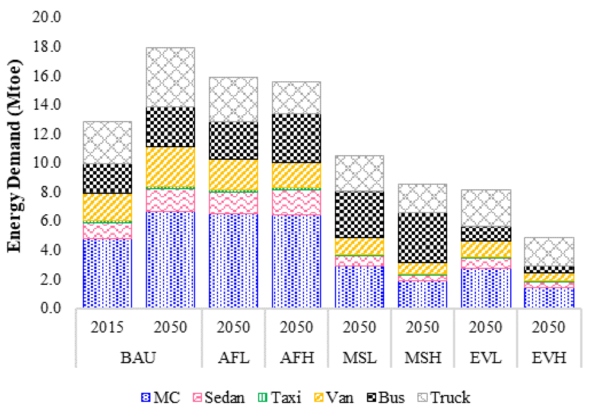

Fig. 13. Energy demand by vehicle types in Vietnam.

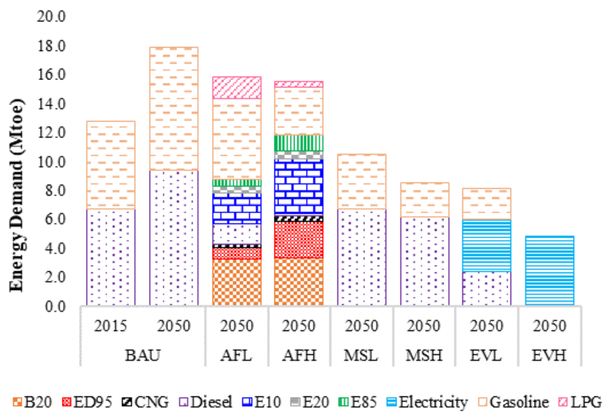

Fig. 14. Energy demand by fuel types in Vietnam.

The energy demand of diesel and gasoline in the road transport in Vietnam would be 9.39 Mtoe and 8.52 Mtoe, respectively, in the BAU scenario in 2050. The fuel types used in the AFL and AFH scenarios are more diversified than the BAU scenarios. In the AFH scenario in 2050, the demand for conventional diesel and gasoline will be reduced from the BAU scenario by 98.51% and 61.49%, respectively. Nonetheless, the demand for CNG, LPG, E20, and B20 fuels will be 0.41 Mtoe, 0.46 Mtoe, 0.53 Mtoe, and 3.4 Mtoe, respectively, in the AFH scenario.

5.2 GHG Emissions

The selected GMS countries, as a whole, emitted 148.42 Mt-CO_2eq of GHG in the road transport in 2015 and GHG emissions will increase to 212.54 Mt-CO_2eq by 2050 in the BAU scenario. Thailand will be responsible for more than 50% of the total GHG emissions in this particular sub-sector. Vietnam, Cambodia, and Lao PDR will be responsible for 25.6%, 18.9%, and 3.96%, respectively. The presence of alternative fuels in the AFL and AFH scenarios will be able to reduce the GHG emissions from the BAU scenario in 2050 by 18.73% and 26.15%, respectively.

The transport modal shifting from private to public such as buses and railway will result in GHG mitigation of 41.63% and 52.24% in the MSL and MSH scenarios, respectively, from the BAU scenario in 2050. In the EVL and EVH scenarios, the GHG emissions in the road transport of the selected GMS countries will be mitigated from the BAU scenario in 2050 by 50.01% and 69.75%, respectively. In the EVL scenario in 2050, 42% of the GHG emissions will come from the power sector which produces electricity for the demand of electric vehicles in the scenario. In the EVH scenario, 95.3% of the GHG emissions will be originated from the power sector. Even though, adding the GHG emissions from the power sector resulting from the EVs to the road transport sub-sector, the EVH scenario will have the lowest GHG emissions compared to the other scenarios.

Figure 15 shows the GHG emissions in the road transport in the selected GMS countries as a whole, while Figure 16 illustrates the GHG emissions from the power sector corresponding to the electricity production used in the road transport.

5.2.1 Cambodia

The GHG emissions in the road-transport in Cambodia will be 40.17 Mt-CO_2eq in 2050 in the BAU scenario. Figure 17 shows the GHG emissions by vehicle types in the road transport in Cambodia.

Motorcycles will be the vehicle technology that will cause the majority of the GHG emissions in the BAU scenario in 2050. Buses will be responsible for 2.2% of the total GHG emissions in the road transport in Cambodia in the BAU scenario. The GHG emissions in the road transport in Cambodia will be reduced from the BAU scenario by 2050 by 17.07% in the AFL scenario, whereas in the MSL and EVL scenarios, the emissions will be reduced by 44.15% and 36.85%, respectively. In the BAU scenario in 2050, the GHG emissions caused by the use of diesel and gasoline would be 20.66 Mt-CO_2eq and 19.5 Mt-CO_2eq, respectively.

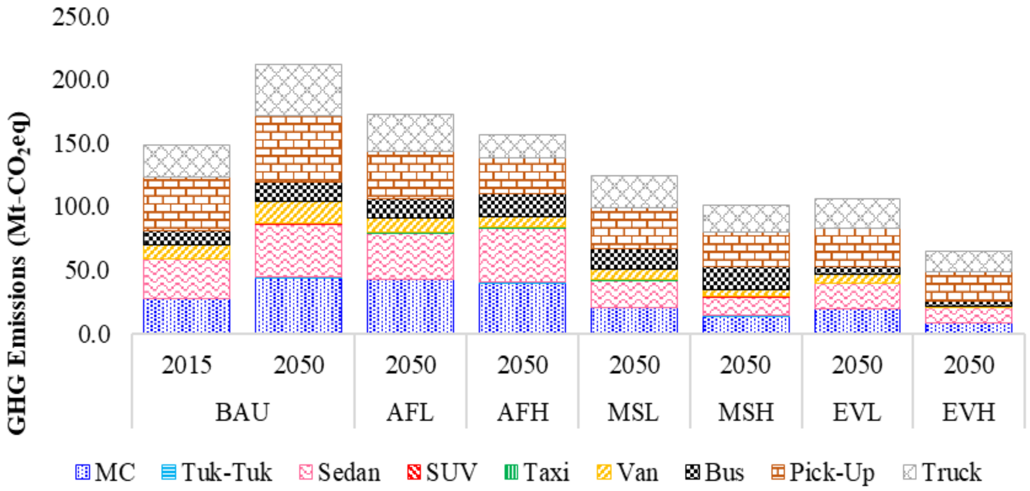

Fig. 15. Total emissions in the road transport sub-sector in the selected GMS countries.

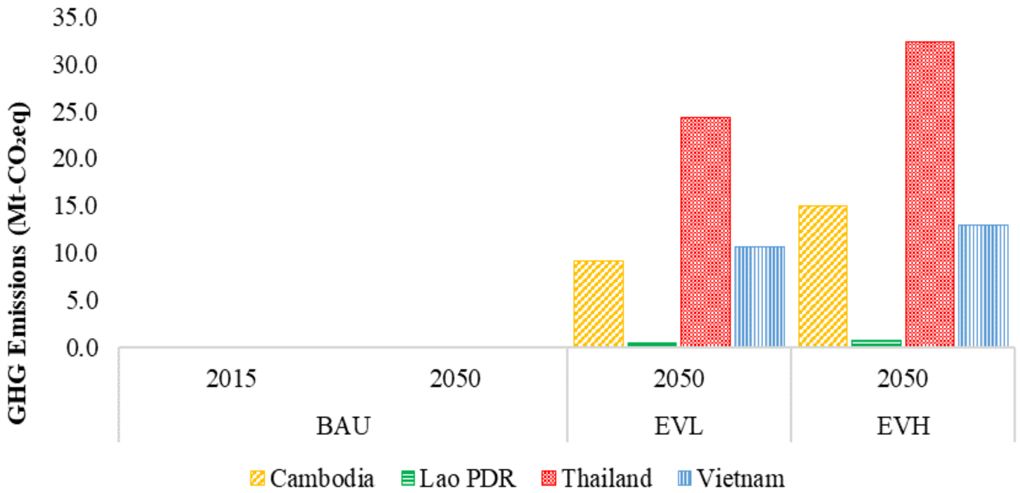

Fig. 16. GHG emissions from electricity generation for EVs.

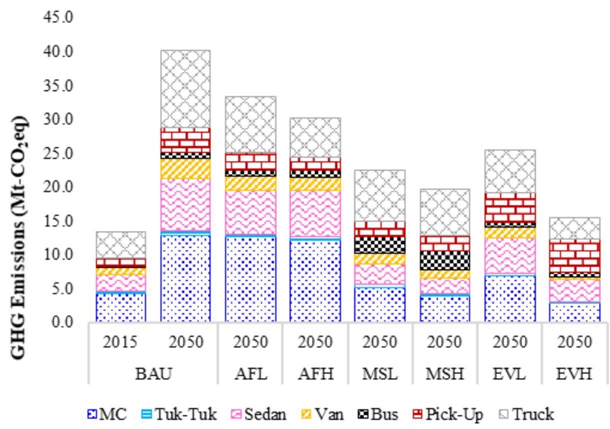

Fig. 17. GHG emissions by vehicle types in Cambodia.

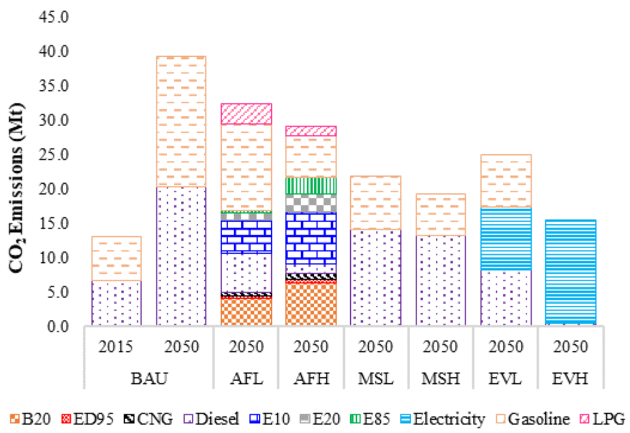

Fig. 18. GHG emissions by fuel types in road transport in Cambodia

The GHG emissions caused by diesel in the EVH scenario would be 0.43 Mt-CO_2eq, and the rest of the GHG emissions in the scenario will be caused by producing electricity for the electric vehicles as can be seen from Figure 18.

5.2.2 Lao PDR

The GHG emissions in Lao PDR in the road transport will increase from 3.04 Mt-CO_2eq in 2015 to 8.42 Mt-CO_2eq by 2050 in the BAU scenario. Despite the small number of trucks in the country, by 2050 in the BAU scenario, the GHG emissions caused by the trucks will have the biggest share (36.73%) among the total GHG emissions in the sector. In the AFH, MSH, and EVH scenarios, the GHG emissions will be mitigated from the BAU scenario in 2050 by 2.86 Mt-CO_2eq, 3.96 Mt-CO_2eq, and 7.53 Mt-CO_2eq, respectively. The vehicle technology to mitigate the most GHG emissions in the AFH scenarios is truck, whereas, in the MSH and EVH scenarios, the technology is motorcycle as can be seen in Figure 19.

By 2050, the GHG emissions in road transport in Lao PDR in the BAU scenario will be caused by 65% of diesel and 35% of gasoline. Nevertheless, because of the measures in the AF scenarios, the GHG emissions in the AFL scenario in 2050 will be caused by 29.77% of B20 fuel, 33.38% of diesel, 0.68% of E10 fuel, and 8.24% of LPG. In the EVL scenario in the same year, the GHG emissions caused by producing electricity for electric vehicles will be responsible for 91.92% of the total GHG emissions in that scenario. Figure 20 illustrates the GHG emissions by fuel types in road transport in Lao PDR.

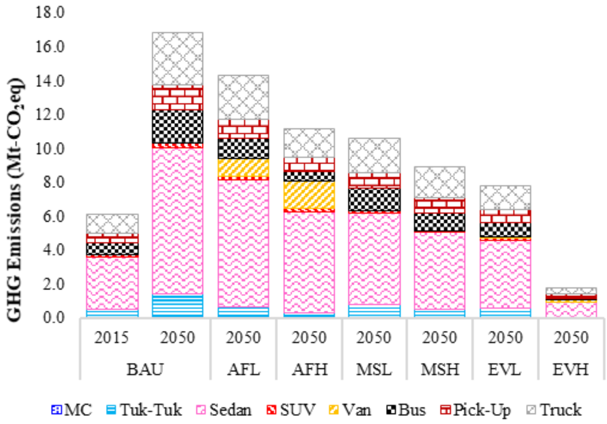

Fig. 19. GHG emissions by vehicle types in Lao PDR.

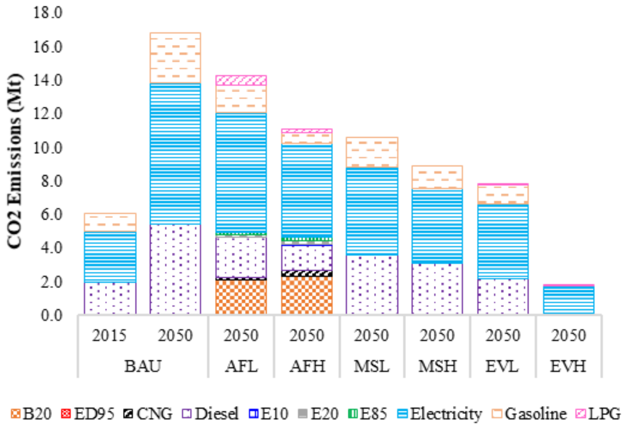

Fig. 20. GHG emissions by fuel types in Lao PDR.

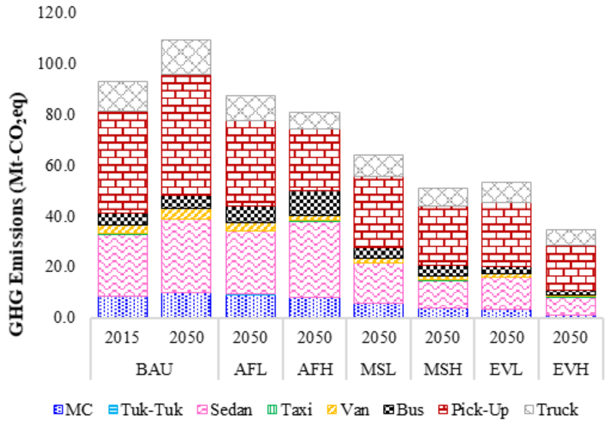

Fig. 21. GHG emissions by vehicle types in Thailand.

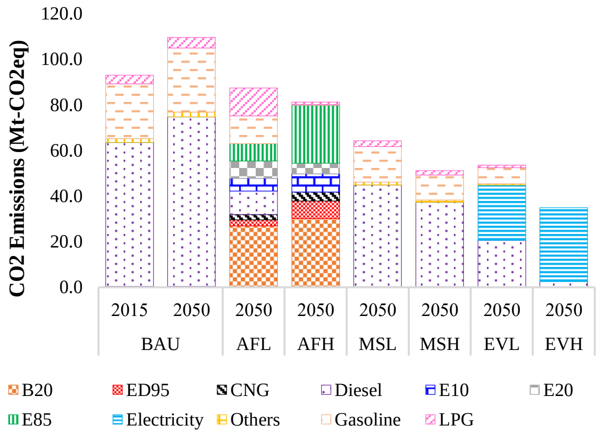

Fig. 22. GHG emissions by fuel types in Thailand.

5.2.3 Thailand

The road transport of Thailand will have the largest GHG emissions among the four countries. By 2050, GHG emissions in the road transport in Thailand will shoot up from 93.02 Mt-CO_2eq in 2015 to 109.54 Mt-CO_2eq in the BAU scenario, indicating an AAGR of 0.5%. The main vehicle technology that will emit the most GHG in the road transport will be the pick-ups, accounting for 43.15%. Despite a large number of motorcycles in the country, the GHG emissions in the BAU scenario by 2050 of the motorcycles will be only 9.08% of the total GHG emissions in the sector. By 2050, GHG emissions in the AFL, MSL, and EVL scenarios will be mitigated from the BAU scenario by 20.18%, 41.35%, and 50.09%, respectively. The GHG emissions by vehicle types in all scenarios in the road transport in Thailand can be found in Figure 21.

Figure 22 represents the GHG emissions by fuel types in the road transport in Thailand. In terms of fuel, the GHG emissions in the road transport will be caused by various fuels such as diesel, gasoline, LPG, and CNG. By 2050 in the BAU scenario, the use of diesel and gasoline will result in GHG emissions of 74.37 Mt-CO_2eq and 28.14 Mt-CO_2eq, respectively. However, in the AFH scenario, the GHG emissions caused by the use of diesel in road transport in Thailand will drop to zero by 2050. In the MSH scenario, the GHG emissions caused by the use of diesel and gasoline will be reduced from the BAU scenario by 50.2% and 61.23%, respectively. In the EVH scenario in 2050, the GHG emissions caused by the use of electric vehicles (including BEVs, PHEVs, and HEVs) in the road transport in Thailand will amount to 32.41 Mt-CO_2eq.

5.2.4 Vietnam

In Vietnam, the GHG emissions in the road transport sub-sector will rise from 38.99 Mt-CO_2eq in 2015 to 54.42 Mt-CO_2eq by 2050 in the BAU scenario (see Figure 23).

In the AFH, MSH, and EVH scenarios, the GHG emissions in the sector will be mitigated from the BAU scenario by 14.4 Mt-CO_2eq, 28.14 Mt-CO_2eq, and 41.35 Mt-CO_2eq, respectively, in 2050. The majority of the GHG emissions in the sector in the BAU scenario will be caused by motorcycles (36.07%) followed by trucks (23.04%). In comparison to the BAU scenario, trucks will be achieving the most GHG emissions reduction in the AFH scenario. However, in the MSH and EVH scenarios, motorcycles will be the vehicle technology to have the biggest emissions mitigation in the road transport in Vietnam from the BAU scenario in 2050.

From the fuel type perspective, with the presence of alternative fuels, the GHG emissions in the AFH scenario that will be caused by the use of conventional diesel and gasoline will collectively be reduced from the BAU scenario by 44.66 Mt-CO_2eq in 2050 as illustrated in Figure 24.

On the other hand, in the EVH scenario, the GHG emissions caused by the use of conventional diesel will be reduced from the BAU scenario by 99.8%. Nonetheless, the GHG emissions that will be caused by the electricity generation for the use of electric vehicles in the EVH scenario in 2050 will amount to 13.01 Mt-CO_2eq.

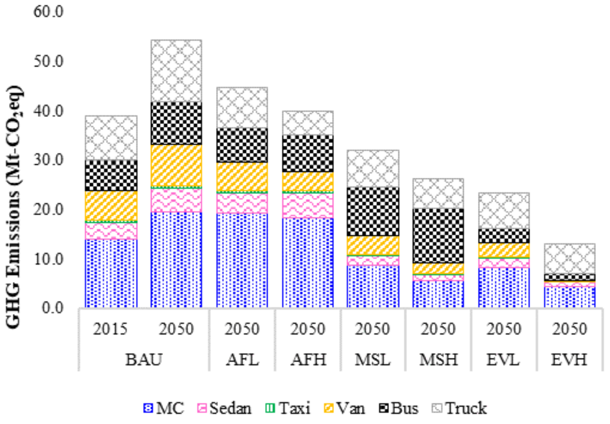

Fig. 23. GHG emissions by vehicle types in Vietnam.

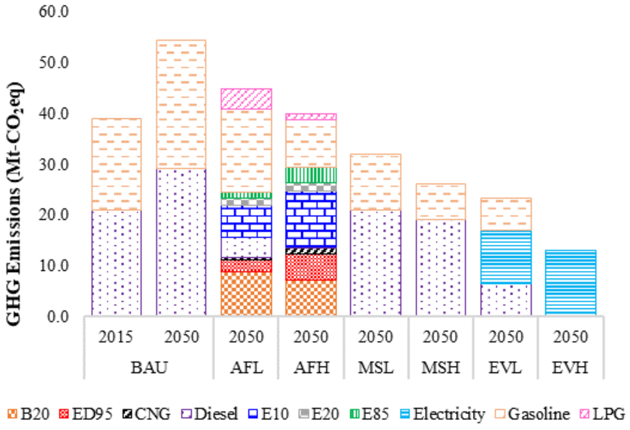

Fig. 24. GHG emissions by fuel types in Vietnam.

5.3 Marginal Abatement Cost

The MAC study considers the benefits of biofuel-fired vehicles and EVs in the selected GMS countries. Figure 25 presents the MACC of some of the measures in the EVH scenario in the road transport sub-sector in the selected GMS countries during 2015-2050.

The results suggest that the cumulative GHG mitigation in the selected GMS countries can be obtained during 2015-2050 from Battery Electric (BE) sedans, BE motorcycles, BE buses, BE trucks, E20 sedans, E10 motorcycles, B20 buses, and B20 trucks would collectively amount to 1636.12 Mt-CO_2eq.

The replacement of diesel trucks with B20 trucks in Lao PDR, Vietnam, and Thailand will result in the lowest, second lowest, and third-lowest cumulative MACs during 2015-2050 amongst other measures included in the MAC analysis. This is due to the large saving in fuel cost by using B20 trucks. However, their corresponding cumulative GHG abatement is also low. On the other hand, the replacement of gasoline sedans with BE sedans will result in reasonably low cumulative MACs for all four countries and high corresponding GHG abatement during 2015-2050. This is because the fuel cost saving is higher than the capital cost of the BE sedans. Similarly, the replacement of gasoline motorcycles with BE motorcycles would result in high cumulative GHG abatement during 2015-2050 for the selected GMS countries. The GHG abatements of BE motorcycles will account for 86.64 Mt-CO_2eq in Cambodia, 21.58 Mt-CO_2eq in Lao PDR, 141.34 Mt-CO_2eq in Thailand, and 244.22 Mt-CO_2eq in Vietnam. Nonetheless, their corresponding cumulative MACs are also very high. According to MACC in Figure 25, the technologies that the government in the selected GMS countries should focus on to achieve large GHG mitigation while keeping the expenditure low would be BE sedans, BE trucks, and BE buses.

6. CONCLUSION

This study observed the effects of alternative fuels, the modal shift from private to public transportation, and electric vehicles on the GHG emissions in the road transport in the selected GMS countries: Cambodia, Lao PDR, Thailand, and Vietnam. Besides the BAU scenario, this study developed three main different scenarios namely, Alternative Fuel (AF), Modal Shift (MS), and Electric Vehicle (EV) using the Low Emission Analysis Platform (LEAP) model. Each of the scenarios was divided into two levels namely, low-ambition and high-ambition. The findings of the study suggest that when comparing the low-ambition scenarios (AFL, MSL, and EVL), the total GHG mitigation from the BAU scenario in the selected four countries is found to be the largest in the EVL scenario in 2050. In addition, when the high-ambition scenarios were compared, the largest GHG mitigation from the BAU scenario in 2050 could be found in the EVH scenario which would amount to 148.24 Mt-CO_2eq. In addition, the MAC analysis also recommends that the replacement of conventional vehicles with BEVs will result in low MAC and high GHG abatement. Even though, the penetration rates considered in this study are rather dynamic than statics, this study would provide a clear insight about the effects of biofuel, transport modal shifting, and electric vehicles on energy consumption and emissions. It helps the policymakers making appropriate decision when applying or revising the transportation master plan in these four countries.

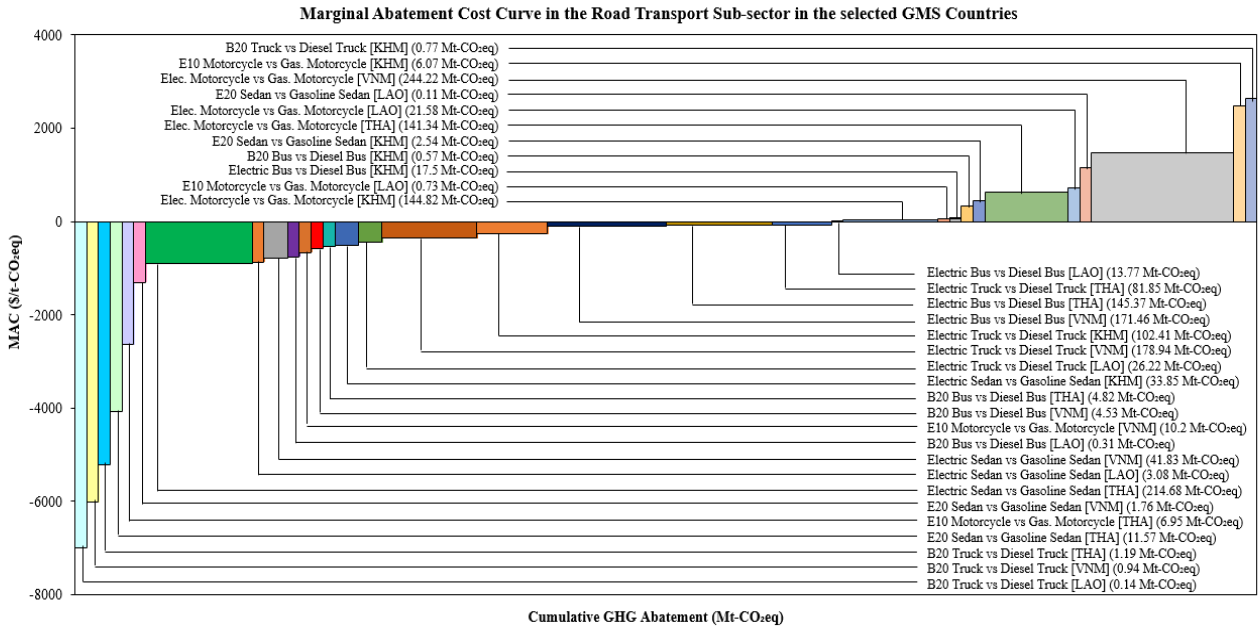

Fig. 25. MACC of some measures in the road transport sub-sector in the selected GMS countries.

Thus, it can be concluded that electric vehicles (BEVs, PHEVs, and HEVs) would have the highest potential to mitigate the GHG emissions in the road transport in the selected GMS countries collectively than the fuel-switching and the modal shifting measures in 2050. If the electricity supply for EVs is produced from cleaner energy, GHG emissions will be lower than those emitted from the internal combustion engines. However, the modal shifting measures also showed a desirable amount of GHG emissions mitigation compared to the electric vehicle measures. Thus, the common policy recommendations for the selected GMS countries are as follows:

- The transport sector master plan of each country should be revised to increase the development of biofuels and modal shift.
- Encourage people to change their commuting modes to public transportation by introducing incentives and subsidies.
- Raising awareness among the citizen of the danger of conventional fuels. This will, in return, encourage people to shift to biofuels.
- There should be incentives in terms of the fuel price reduction applied to biofuels.
- Each country should develop its vehicle standards or follow well-known vehicle standards such as the Euro 5 and Euro 6.
- The ban on the import of used vehicles should be adopted from 2025 onward.
- Incentives should be provided to the individuals who use standard-compliant or electric vehicles.
- The policymakers should strive for the investments of electric vehicle and biofuel companies.
- Each country should be well-prepared in advance for the EV charging system that will have high demand in the future.
- The electricity supply for EVs should be produced from green energy, e.g., 90% to 100% of electricity supply for EV charging stations should be produced using solar, biomass, wind, or hydrogen.

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