Estimation of Fuel Consumption in Road Transport: A Case Study of Ethanol Bus in Thailand

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In Thailand, road transport has completely dominated energy consumption throughout the years because of insafficent transportation networks of rail and water. Inevitably, greenhouse gas emission from transportation sector, especially road transport, has soared over recent years. In accordance to global warming concern throughout the world, Thailand has taken various adaptation and mitigation measures, especially the strong policy push to use carbon-neutral biofuel as transportation fuel due to Thailand competitive advantage in agriculture. Clear targets of bioethanol and biodiesel have been set in the recent National Alternative Energy Plan (2008-2022). With challenging target of 9 million liters/day ethanol consumption by 2022, various strategies have been planned and undergone various stages of implementation.

In this study, a case study of ethanol bus technology was investigated by recourse to energy demand modeling. Necessary data, such as a number of vehicles (NV) for various vehicle types, vehicle kilometer of travel (VKT) and fuel economy (FE) was collected, with reasonable assumptions made for those unavailable data, to construct predicative energy demand model. Scenario analysis on ethanol bus introduction was conducted to assess reduction of fossil fuel by increasing the use of ethanol to achieve ethanol consumption target in 2022.

Key Words : *fuel consumption, ethanol bus, GHGs emission reduction, transport sector in Thailand*

1. INTRODUCTION

Thailand has strived to reduce fossil fuel dependency by using indigenous biofuel. In Recent National Alternative Energy Strategic Plan (2008-2022) , 4% biofuel from 20% of alternative fuel used in 2022 was set as the targets. This aims 9 million liters/day of bioethanol and 4.5 million liters/day of biodiesel consumption by 2022.

In order to assess the possibility of achieving these targets, previous study has utilized energy demand model to evaluate various policy implementation[1), 2)]. Commercially available bottom-up program called Long range Energy Alternatives Planning system (LEAP) was employed with necessary data input, such as a number of vehicles (NV) for various vehicle types, vehicle kilometer of travel (VKT) and fuel economy (FE). Where data unavailable, reasonable assumption was required to estimate total energy demand in transportation sector. Three scenarios, namely promotion of E20 (ethanol-blended gasoline at 20%), ban of ULG91 (unleaded gasoline with octane of 91) and aggressive promotion of E85 (ethanol-blended gasoline at 85%), were investigated in comparison to the BAU (business as usual) reference case. The results revealed that only aggressive promotion of E85 can achieve the target of 9 ML/d consumption by 2022 but with the great expense of subsidy on new Flexible Fuel Vehicles (FFVs) and parts modification on non-FFVs. Promotion of E20 did not require much subsidy since cost of parts modification was minimal, and supporting policy to reduce excise tax by 5% lower than the conventional vehicle has already been enforced. However, the increase in ethanol consumption from E20 promotion was not much. Lastly, a ban of ULG91 could effectively increase ethanol consumption with reasonable subsidy for parts modification of impacted vehicles, mostly motorcycles. Although a ban of ULG91 could not raise ethanol consumption to the target of 9 ML/d by 2022, the policy can jump start the ethanol demand by approximately 2 ML/d[1].

Thus, in this study, scenario analysis on ethanol bus introduction was conducted to assess reduction of fossil fuel by increasing the use of ethanol to achieve ethanol consumption target in 2022.

2. METHODOLOGY

In order to analyze energy use pattern in transportation sector with capability to predict energy demand, bottom-up approach is undertaken due to its capability in accounting for the flow of energy based on simple engineering relationship, such as traveling demand, fuel consumption and vehicle numbers. Among many others, Long-range Energy Alternatives Planning (LEAP) system will be utilized to construct the energy demand model in this study[3].

The energy demand function in transportation sector can be modeled as described in (1).

$$ED_{ij} = NV_{ij} \cdot VKT_j \cdot FE_{ij} \quad (1)$$

where,

ED_{ij} ; energy demand of fuel type i from vehicle type j [liter/year]

NV_{ij} ; number of registered vehicle type j that uses fuel type i [number of vehicle]

VKT_j ; average distances traveled by vehicle type j in a year of interest [km/year]

FE_{ij} ; fuel economy of registered vehicle type j that uses fuel type i [liter/km]

In other words, the energy demand in the transportation sector can be determined by integrating the results over every fuel type i and vehicle type j, as follows. Firstly, the number of registered vehicle (NV) is estimated from historical record from Transport Statistics Sub-Division, Department of Land Transport (DLT)[4]. The data can be fitted with economic and population growth[1), 2), 5]. However, since necessary data like Vehicle Kilometer of Travel (VKT) is not sufficiently available, reasonable detailed assumptions must be applied [6),7]. For other data like Fuel Economy (FE), it can be extrapolated as the function of engine size, engine technology and fuel used, which are dependent on vehicle type and fuel proportion of the vehicle owner. Finally, the validation of energy demand model with the historic supply record will be calibrated before scenario analyses are conducted

Business-as-usual (BAU) assumptions were formulated based from previous studies and related governmental transportation policies[2),8] between 2010 and 2030. Ethanol promotion policies in both gasoline and diesel sectors were taken into account in order to estimate various fuels needed by different vehicle categories, especially in the diesel sector. The ethanol consumption target set in Thailand Alternative Energy Strategic Plan was benchmarked in order to rationalize certain scenario analyses of interest. Benefits were highlighted in terms of increase in ethanol consumption and GHG emission reduction by introduction of ethanol bus technology.

3. MODEL DEVELOPMENT

As shown in (1), energy demand function in the transportation sector can be constructed from knowledge of vehicle stock, vehicle kilometer of travel and fuel economy. A brief summary of the energy model construction is discussed here, and more details can be found elsewhere[6), 7].

(1) Model setup

Vehicle types can be re-categorized from DLT classification for the purpose of LEAP calculation, as shown in the Table 1. Note that the agriculture vehicle, utility vehicle and automobile trailer are not considered in this work because they consume small fraction of energy. For each vehicle categories, three general vehicle population models were fitted as follows.

1. Exponential function[9]
2. Logistic Regression function[2), 10), 11), 12]
3. Combined function of the two above

where detailed functional form can be referred elsewhere[6]. Table 2 shows vehicle population models (with R2 fitting parameter) for all vehicle types in Bangkok and provincial regions, with graphical fitting shown in Fig. 1 for the cases of fixed route bus only.

Table 1 Vehicle re-classification in leap model from DLT data.

A. Total vehicle under motor vehicle act		B. Total vehicle under land transport act	
MV.1 Not more than 7 passengers	PC01 passenger car	Bus	
MV.2 Microbus & Passenger Van		- Fixed Route Bus	BUS01
MV.3 Van & Pick Up	PC02	- Non Fixed Route Bus	BUS02
MV.4 Motortricycle	PC03 motor tri-cycle	- Private Bus	BUS03
MV.7 Fixed Route Taxi (Subaru)		Small Rural Bus	sBus04
MV.8 Motortricycle Taxi (Tuk Tuk)		Truck	
MV.6 Urban Taxi	PC04 taxi	- Non Fixed Route Truck	Truck01
MV.5 Interprovincial Taxi	PC05 Commercial rent car	- Private Truck	Truck02
MV.9 Hotel Taxi			
MV.10 Tour Taxi			
MV.11 Car for Hire			
MV.12 Motorcycle	PC06 Motor cycle		
MV.17 Public Motorcycle			
MV.13 Tractor	-		
MV.14 Road Roller			
MV.15 Farm Vehicle			
MV.16 Automobile Trailer			

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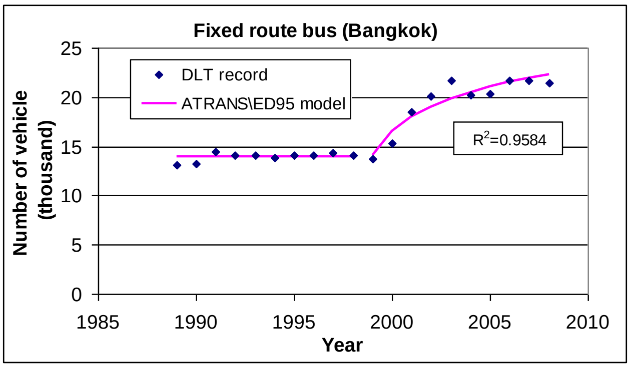
Table 2 Vehicle population model for all vehicle types in (A) Bangkok and (B) Provincial regions.

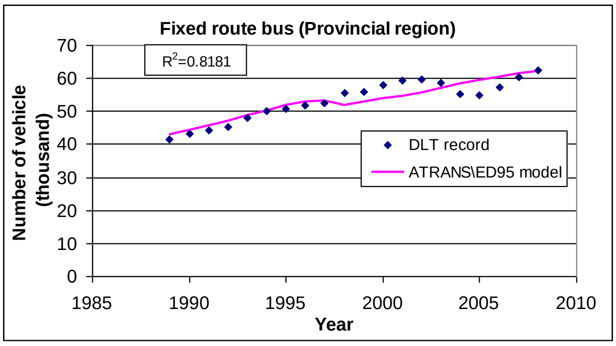
(a)	N_vehicle Bangkok (GDPpCap)	R^2
PC01 private passenger car	$ln\left(\frac{VO}{0.812-VO}\right)=1.3273\,lnGDPpCap-17.8210$	0.8632
PC02 pickup	$ln\left(\frac{VO}{0.5-VO}\right)=2.2175\,lnGDPpCap-28.005$	0.7992
PC03 motor tri-cycle	$NV=16686.9 \quad yr\le 2001$ $=(unusal) \quad 2002\le yr\le 2004$ $NV=1265.6\,ln(yr-\tau)+12527 \;;\; \tau=2004$ $yr\ge 2005$	0.9681 (2005-2008)
PC04 taxi	$lnVO=2.6119\,lnGDPpCap-35.373$	0.7811
PC05 commercial rent car	$NV=-178.6\,ln(yr-\tau)+2399.4; \;;\; \tau=1988$	0.4052 (1989-1998)
PC06 motor cycle	$ln\left(\frac{VO}{0.6-VO}\right)=1.5731\,lnGDPpCap-20.2060$	0.7642
Bus01 fixed route bus	$NV=13970 \quad yr\le 1998$ $NV=3585.8\,ln(yr-\tau)+14061 \;;\; \tau=1998$ $yr\ge 1999$	0.9584
Bus02 non fixed route bus	$NV=\left(1-0.5071\cdot e^{-0.0323*(yr-\tau)}\right)\cdot\left(1786.9\,ln(yr-\tau)+6724.6\right)$ $\tau=1988$	0.9057
Bus03 private bus	$NV=\left(0.5071\cdot e^{-0.0323*(yr-\tau)}\right)\cdot\left(1786.9\,ln(yr-\tau)+6724.6\right)$ $\tau=1988$	0.7376
sBus04 small rural bus	-	-
Truck01 non fixed route truck	$NV=\left(1-0.7868\cdot e^{-0.0155*(yr-\tau)}\right)\cdot\left(20577\,ln(yr-\tau)+56314\right)$ $\tau=1988$	0.9136
Truck02 private truck	$NV=\left(0.7868\cdot e^{-0.0155*(yr-\tau)}\right)\cdot\left(20577\,ln(yr-\tau)+56314\right)$ $\tau=1988$	0.5143

(b)	N_vehicle Provincial (GDPpCap)	R^2
PC01 private passenger car	$ln\left(\frac{VO}{0.812-VO}\right)=2.5007\,lnGDPpCap-31.025$	0.8842
PC02 pickup	$ln\left(\frac{VO}{0.5-VO}\right)=2.5491\,lnGDPpCap-30.388$	0.8244
PC03 motor tri-cycle	$VO=0.0005188$	0.0041
PC04 taxi	$ln(VO)=-2.2974\,lnGDPpCap+14.4340$	0.5965
PC05 commercial rent car	$ln(VO)=1.8111\,lnGDPpCap-31.1840$	0.6464
PC06 motor cycle	$ln\left(\frac{VO}{0.6-VO}\right)=2.3609\,lnGDPpCap-26.678$	0.7021
Bus01 fixed route bus	$ln(VO)=0.2530\,lnGDPpCap-9.7824$	0.8181
Bus02 non fixed route bus	$ln(VO)=1.6778\,lnGDPpCap-26.689$	0.9533
Bus03 private bus	$ln(VO)=0.0659(yr-\tau)-10.422$ $\tau=1988$	0.9620
sBus04 small rural bus	$ln(VO)=-0.0049\,(yr-\tau)^2+0.0604\,(yr-\tau)-7.9501$ $\tau=1988$	0.8942
Truck01 non fixed route truck	$ln(VO)=0.0787(yr-\tau)-8.1426$ $\tau=1988$	0.9842
Truck02 private truck	$ln(VO)=0.3046\,ln(yr-\tau)-5.6463$ $\tau=1988$	0.9574

where,
GDPpCap; GDP per capita [Baht]
Pop; Population [person]
yr ; Year, which is the parameter of time
VO = fuel type



(a)



(b)

Fig.1 Vehicle ownership model for (a) Bangkok fixed route bus and (b) Provincial fixed route bus.

Next required parameter is the vehicle kilometer of travel (VKT), which is a parameter to measure vehicles' activities on road, which is dependent on the vehicle type and its driven area. Moreover, it should be noted that the VKT is not constant with time because the gross road distance and/or traffic conditions changes. Unfortunately, the VKT data in Thailand is not recorded on a regular basis, and the statistics survey works has not been frequently conducted. To the best of the authors' knowledge, there are only two rather complete survey results, from 1997[13)] and 2008[14)], as altogether shown in Fig. 2. Extrapolation and averaging from these two data sources were conducted in the LEAP model[6)].

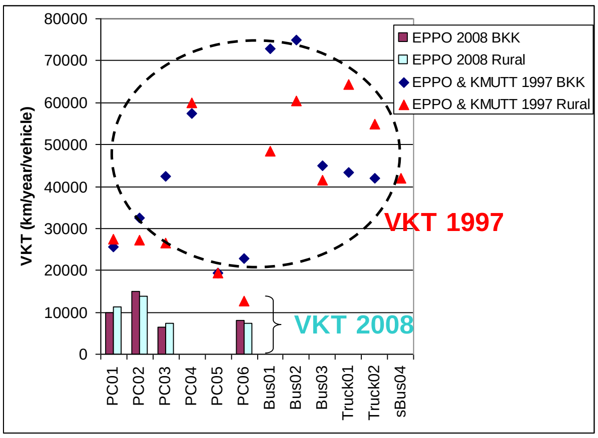


Fig.2 Available VKT data in Thailand from transport survey.

Last parameter is fuel economy (FE), which clearly depends on the vehicle size, vehicle type, vehicle's powertrain technology (engine type) and fuel type. A parameter, called Device Share (DS), was introduced to account for fuel sharing when two fuel types are used, such as gasohol (ethanol-blended gasoline), bi-fueled CNG (gasoline and CNG) and diesel dual fuel (DDF: diesel and CNG). When CNG is used in certain vehicle types, the FE was approximated from[15), 16)]. Table 3 summarizes FE of each vehicle type used in LEAP model for Bangkok and provincial regions.

Table 3 Approximated fuel economy of all vehicle types in (A) Bangkok and (B) Provincial regions

(a) **Bangkok** km/litre and km/litre for CNG	Single fuel engine				Dedicated gas engine	
	Spark ignition engine			Diesel engine	LPG	CNG
	Gasoline	E10	E20			
PC01	10.62*	11.30*	9.85**	11.44*	9.87*	10.85*
PC02	10.00*	9.64**	9.28**	11.21*	11.57*	11.33*
PC03	10.92**	10.52**	10.13**	12.00**	9.71*	9.29*
PC04	10.58**	10.20**	9.82**	11.63**	9.83**	10.81**
PC05	11.83**	11.40**	10.97**	13.00**	10.99**	12.08**
PC06	32.77*	29.24*	-	-	-	-
Bus01	2.18**	2.10**	2.03**	2.40*	2.03**	1.86*
Bus02	2.09**	2.01**	1.94**	2.30**	1.94**	2.13**
Bus03	2.09**	2.02**	1.95**	2.31**	1.95**	2.14**
sBus04	-	-	-	-	-	-
Truck01	2.57**	2.48**	2.38**	2.83*	2.39**	2.63**
Truck02	2.22**	2.14**	2.06**	2.44**	2.07**	2.27**

(b) **Province** km/litre and km/litre for CNG	Single fuel engine				Dedicated gas engine	
	Spark ignition engine			Diesel engine	LPG	CNG
	Gasoline	E10	E20			
PC01	12.28*	12.43*	11.40**	11.96*	11.03*	10.04*
PC02	11.88*	12.07*	11.02**	12.04*	11.00*	12.42*
PC03	16.16*	15.57*	14.99**	16.06**	12.18*	9.29**
PC04	12.09**	11.66**	11.22**	12.02**	11.03**	11.26**
PC05	10.82**	10.43**	10.04**	10.75**	9.87**	10.08**
PC06	25.75*	25.92*	-	-	-	-
Bus01	4.18**	4.03**	3.88**	4.15*	3.81**	3.12*
Bus02	4.37**	4.21**	4.06**	4.34**	3.99**	4.07**
Bus03	4.35**	4.19**	4.04**	4.32**	3.97**	4.05**
sBus04	4.71**	4.54**	4.37**	4.68**	4.29**	4.38**
Truck01	4.05**	3.90**	3.76**	4.02*	3.69**	2.01*
Truck02	4.68**	4.51**	4.34**	4.65**	4.27**	4.36**

(2) Model calibration

From all the parameters described above, assumptions and correction factor on the recent fuel price hike have been taken into account. The validation of the model capability for the base year 2006 and other years against the total energy consumption from DEDE[17)] shows reasonably good agreement with some error in the individual consumption of gasoline and diesel, as shown in Fig. 3. Detailed inspection reveals that the difference mainly comes from the gas fractions (LPG and CNG) during the recent fossil fuel crisis, where there was a sharp fuel switching from liquid fossil to subsidized LPG and CNG[12), 13)]. In addition, the registration of gas-conversion vehicles was mandated after the base year of calculation so there were some errors in the number of vehicles using LPG/CNG[4)]. However, this minor impact is beyond the scope of this work, and it is not possible to incorporate into the LEAP setup[3)].

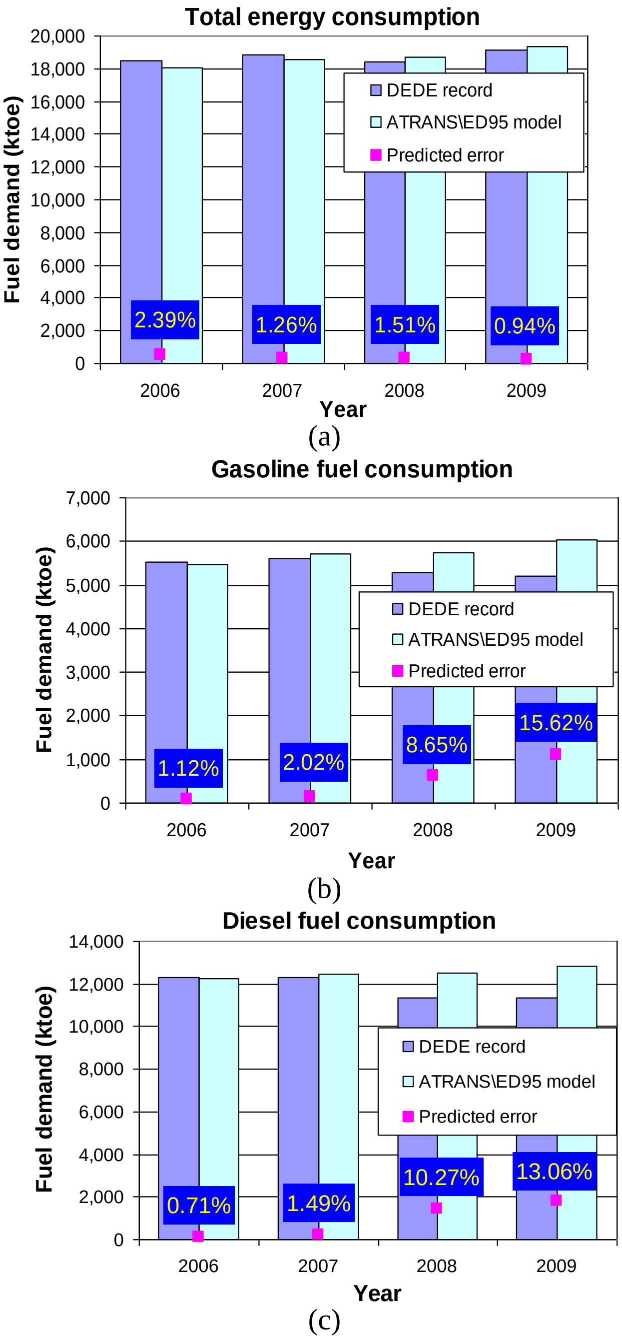


Fig.3 Validation of the energy demand model in term of fuel consumption against fuel sale record in the years 2006–2009 for (a) all fuel types, (b) gasoline and (c) diesel fuels.

(2) Scenario Analysis

The Business-As-Usual assumptions from previous study were followed[1), 2)] with additional assumption according to the governmental plan on fixed route bus sector[8] as follows.

- ✓ New SI vehicles will switch to E20 (20% ethanol blended in gasoline) within 10 years [1), 2)];
- ✓ New SI motorcycles will switch to E10 (10% ethanol blended in gasoline) within 10 years [1), 2)];
- ✓ New fixed route buses will switch to NGV within 10 years[8].

As stated earlier, new ethanol technology for bus would require investment on infrastructure especially on the fuel distribution and dispenser. Hence, the most probable sector for introduction of new technology would be fixed route bus to minimize required infrastructural capital investment. In particular, the scenario analysis focuses on the benefit of substituting NGV bus by ethanol bus in term of energy saving and GHGs emission reduction. Variations of the scenarios are described in Table 4, where the following parameters were investigated.

- ✓ BKK: starting year of ethanol bus introduction (2010 vs 2020)
- ✓ BKK: period of ethanol bus introduction (5 vs 10 years)
- ✓ Provincial: starting year of ethanol bus introduction during a period of 10 years (2015 or 2020)
- ✓

Table 4 Summary of Various Assumptions in BAU and scenario analysis on fixed route bus.

Cases	BKK				Provincial in 10 yrs	
	Starting year		Period (yrs)		Starting year	
	2010	2020	5	10	2015	2020
BAU	-	-	-	-	-	-
A.1	-	√	-	√	-	-
A.2.1(a)	√	-	-	√	-	-
A.2.1(b)	√	-	√	-	-	-
A.2.2(a)	√	-	-	√	-	√
A.2.2(b)	√	-	-	√	√	-

4. RESULTS AND DISCUSSION

(1) Business-As-Usual (BAU) and scenarios analysis

From the BAU reference case, a demand of various fuels in the Thai transportation sector during 2010–2030 was predicted in Fig. 4a. Note that all BAU assumptions during 2010–2020 have resulted in,

- ✓ a switch from E10 to E20 (new passenger cars),
- ✓ a switch from gasoline to E10 (new motorcycles),
- ✓ an increase of CNG from new NGV buses.

As expected, diesel is still a dominating fuel for transportation until 2030. Further insight into diesel consumption shown in Fig. 4b has revealed that small pick-up trucks are still a dominating sector for diesel consumption while diesel consumption in fixed route buses decreases due to the BAU assumption of new NGV buses, which shows a sharp increase in CNG consumption in a fixed route bus sector (both Bangkok and provincial regions), as shown in Fig. 4c. Without any additional ethanol promotion policy, Fig. 8d shows an ethanol demand of 5.5 ML/day in 2022, which is still 3.5 ML/day lower than the 9 ML/day target in the Thailand Alternative Energy Strategic Plan.

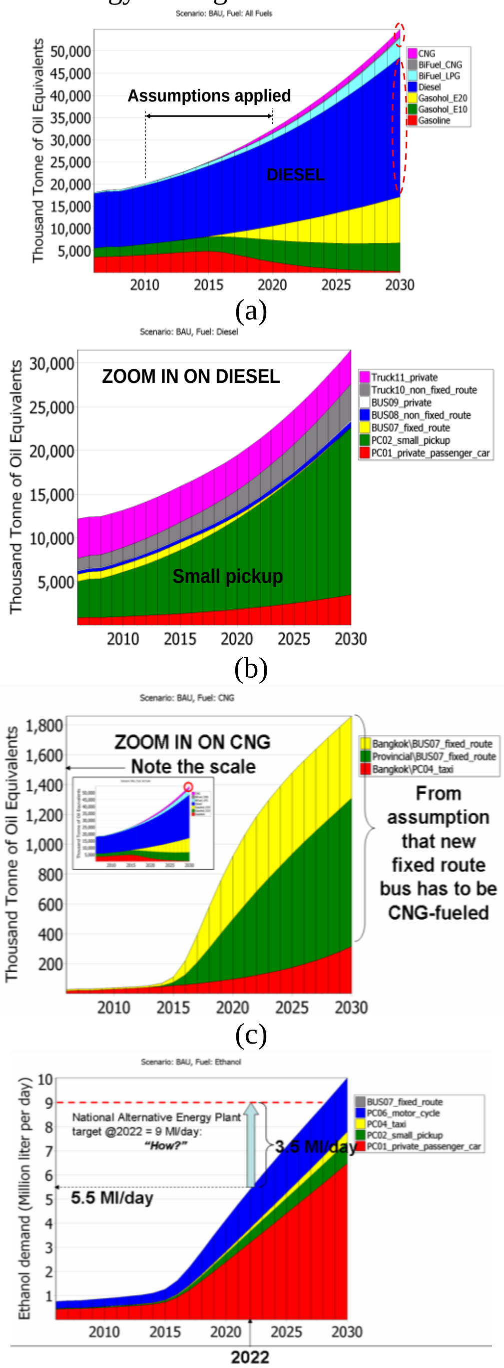
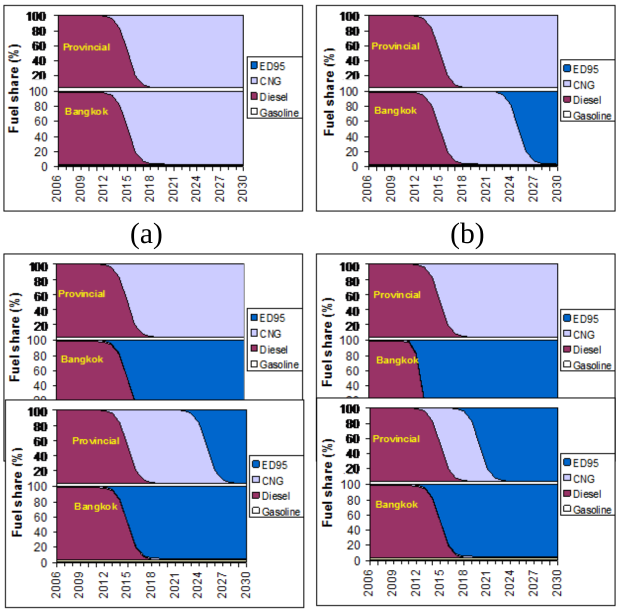


Fig.4 (a) Energy demand prediction for BAU case during 2010–2030 by fuel type with a zoom in on (b) diesel, (c) CNG and (d) ethanol.

With various assumptions for the introduction of ethanol bus in fixed route bus sector listed in Table 4, Fig. 5 shows the composition of new fixed route bus classified by fuel type in both Bangkok and provincial regions, which graphically illustrates and validates various assumptions in Table 4. Clearly for the BAU case, Fig. 5a reflects fuel switching assumption from diesel to CNG during 2010-2020 period. For the case A.1, ethanol bus is introduced in Bangkok region starting from 2020 for a period of 10 years so Fig. 5b shows the fuel switching behavior from CNG to ethanol in Bangkok region without any change in provincial region. For the case of A.2.1(a) with earlier introduction of ethanol bus from 2010 for a period of 10 years in Bangkok region, all previous assumption of new CNG fixed route bus in Bangkok is replaced by ethanol bus, shown in Fig. 5c; whereas, the provincial picture remains unchanged. For the case of A.2.1(b) with shorter period of 5 years introduction than the case of A.2.1(a), the fuel switching from diesel to ethanol occurs faster. With further extension of ethanol bus introduction in provincial region, Fig. 9e shows a fuel switching from CNG to ethanol during 2020-2030; whereas Fig 9f shows an earlier introduction of ethanol bus starting from 2015. Note that Fig. 5 merely shows the new vehicle, where the composition of total vehicle in stock is similar with the stretch in horizontal axis for a new vehicle to get accumulated in the vehicle stock.



(a) (b)

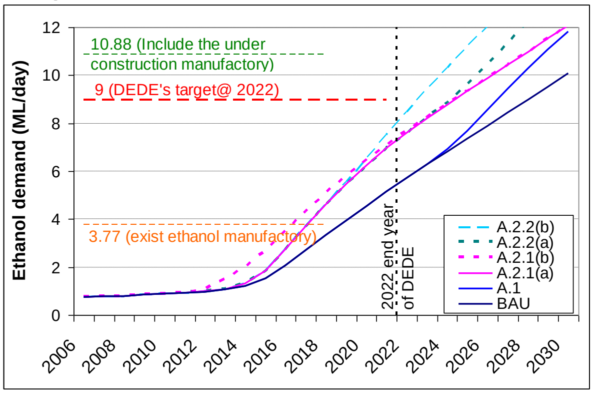
(c) (d)

(e) (f)

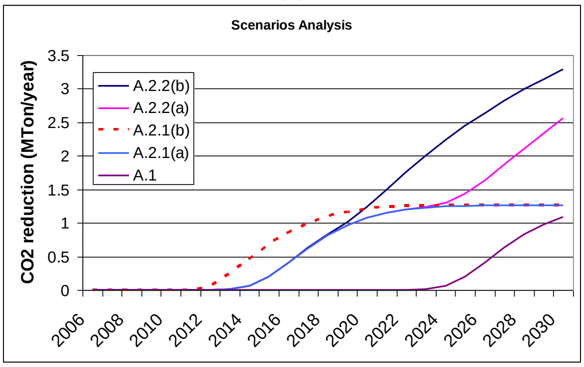
Fig.5 Composition of new fixed route bus by fuel type for (a) BAU, (b) case A.1, (c) case A.2.1(a), (d) case A.2.1(b), (e) case A.2.2(a) and (f) case A.2.2(b).

(2) Implication on Ethanol Demand and GHGs Emission Reduction

Five scenarios, namely A.1, A.2.1(a), A.2.1(b), A.2.2(a) and A.2.2(b) listed in Table 4, were analyzed in term of ethanol demand and GHGs emission with reference to BAU case. As shown in Fig. 4d, BAU case cannot increase ethanol demand as targeted in the National Alternative Energy Plan. With various promotion assumptions on ethanol bus in fixed route bus, Fig. 6a shows that ethanol demand is increased but still not achieving the target of 9 ML/day by 2022. Not only the benefit on increase in ethanol demand, but ethanol bus technology also helps reduce CO2 emission since it is introduced to replace CNG bus. The CO2 emissions are calculated according to the Intergovernmental Panel on Climate Change (IPCC) methodology[18]. The renewable biofuel is treated as carbon-neutral emission while fossil CNG is considered only on the gaseous combustion. The emissions considered here are the exhaust of mobile combustion: CO2 where those of CH4 and N2O are not included here. Fig. 6b clearly shows that a reduction in CO2 emission of up to 1-3 million ton of CO2 per year could be achieved by investigate scenarios for ethanol bus introduction.



(a)



(b)

Fig.6 Prediction of (a) ethanol demand and (b) CO2 emission reduction from all scenarios analyzed.

5. CONCLUSION

Energy demand modeling in road transportation sector was developed from various databases available in Thailand with some necessary assumptions for unavailable data for completion. It must be realized that predicted results may be affected by externalities such as sudden fuel price, consumer behavior and certain policy, which cannot be mathematically taken into account in the commercially available LEAP model setup. Nonetheless, the developed model can be used to provide insight on the impact of certain policy and new technology introduction. The current investigation has analyzed the potential of introducing ethanol bus in the fixed route bus sector in order to realize the ethanol target set in National Alternative Energy Plan, as well as the reduction in GHGs emission with the following results.

Ethanol bus technology can be considered as alternative mechanism to increase ethanol demand as projected by National Alternative Energy Strategic Plan (9 ML/day target in 2022) since ethanol promotion as gasoline blend cannot significantly increase ethanol demand.

Introduction of ethanol bus in a fixed route bus sector in Bangkok during 2010-2020 is the most effective measure to increase ethanol demand by 2022. Introduction in provincial bus at a later period (2015 or 2020) can help increase ethanol demand in a long term.

Ethanol bus substitution into CNG bus in a fixed route bus sector can also help reduce carbon dioxide gas emission up to 1-3 million ton per year.

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