Songklanakarin J. Sci. Technol.
30 (6), 747-754, Nov. - Dec. 2008

Songklanakarin Journal
of Science and Technology
http://rdo.psu.ac.th/sjst

Original Article

Economical and environmental assessments of compressed natural gas for diesel vehicle in Thailand

Prateep Chouykerd[1], Navadol Laosiripojana[1]*, Somchai Chanchaona[2], Chumnong Sorapipatana[1] and Withaya Yongchareon[3]

[1] *The Joint Graduate School of Energy and Environment,*

[2] *Department of Mechanical Engineering, Faculty of Engineering, King Mongkut's University of Technology Thonburi, Thung Khru, Bangkok, 10140 Thailand.*

[3] *Department of Mechanical Engineering, Faculty of Engineering, Chulalongkorn University, Pathum Wan, Bangkok, 10330 Thailand.*

Received 16 January 2008; Accepted 14 August 2008

Abstract

The economic assessments for the use of compressed natural gas as fuel for several types of diesel vehicles, rarely pick up, non-fixed route truck and private truck, were studied. It is noted that two main technologies of diesel natural gas vehicle (NGV), i.e. dedicated retrofit and diesel dual fuel (DDF), were considered in this work. It was found that the dedicated retrofit needs higher investment costs than dual fuel, but can achieve higher diesel saving than dual fuel. In detail, the payback period of dual fuel non-fixed route truck was found to be identical to dual fuel private truck both in the cases of 6 wheel and 10 wheel, while dedicated retrofit non-fixed route truck and private truck are also identical and have longer pay back period than dual fuel due to its higher conversion costs.

This work also presents the emissions released from all types of engines especially green house gas CO_2. It was found that, in the case of light duty diesel i.e. pickup truck, dedicated retrofit emitted high level of CO_2 than both dual fuel and conventional diesel engines. For heavy duty i.e. non-fixed route truck and private truck vehicles, dedicated retrofit emitted a lower level of CO_2 than normal diesel engine. Other pollutants from engine emission, i.e. hydrocarbon (HC), nitric oxide (NO_x), carbon monoxide (CO) and particulate matter, (PM) were also observed. The results indicated that, in the case of light duty diesel, dedicated retrofit engine emits higher levels of HC and CO than diesel engine; in contrast, it emits lower level of NO_x and PM than diesel and dual fuel. Dual fuel emits HC and CO higher than diesel and dedicated retrofit but emits lower level of NO_x and PM than diesel. Lastly, for heavy duty diesel, it was demonstrated that non-fixed route truck and private truck heavy duty dedicated retrofit have potential to reduce emissions of HC, NO_x, CO and PM when compared to normal heavy duty diesel. Engine efficiencies under dual fuel and dedicated retrofit operation were lower than that of the normal diesel engine.

Keywords: natural gas vehicle, dedicated retrofit, diesel dual fuel, emissions, green house gas

1. Introduction

Thailand has been encountering an energy crisis from increasing of energy price. This is due to the limitation of our domestic energy resources, especially fossil fuel, and our increasing energy demand every year. Therefore, Thailand needs to import large amount of energy for activities especially in transportation sector that consumes energy in high level. The Energy Policy and Planning Office (EPPO), Ministry of Energy, Royal Thai Government, forecasted oil demand in the transportation sector will increase rapidly,

*Corresponding author.
Email address: navadol_l@jgsee.kmutt.ac.th

particularly that of diesel oil (EPPO, 2005).

Currently, one of the most promising alternative fuels in Thailand is compressed natural gas (CNG), which can be used in the vehicle instead of diesel oil. In order to use CNG as the fuel, the engine in the vehicle must be modified from the typical one to the gas engine. There are two main technologies related to this modification: dedicated retrofit NGV and diesel dual fuel NGV. The advantage of dedicated retrofit NGV is the high diesel oil saving rate, but this type of NGV can use only natural gas as fuel; therefore, the number of gas stations along the public road plays an important role. In contrast, dual fuel NGV can simultaneously use both natural gas and diesel oil as the fuel but the diesel oil saving rate is lower than with dedicated NGV. Diesel dual fuel engines are based on diesel technology, the main fuel is natural gas but they are designed to start operating with diesel as a 'pilot' ignition source. As the vehicle begins to move to full load performance, the substitute ratio of natural gas can be up to 50%, this makes dual fuel NGV valuable in circumstances where the use of natural gas is desired for environment or economic reasons (ENGVA, 2006). According to a review of the performance testing, dual fuel NGV system performance has lower cylinder pressure and slightly higher total heat release compared to normal diesel operation (Papagainnakis and Hountalas, 2004), whereas the brake specific fuel consumption (BSFC) of dual fuel NGV is considerably higher compared to normal diesel operation (Papagainnakis and Hountalas, 2004). An experimental investigation of engine emission from a test engine that used dual fuel NGV system showed reduction of NO_x and PM but significantly higher CO and HC (Papagainnakis and Hountalas, 2004).

According to the dedicated NGV, this engine is Otto cycle that is operated only on natural gas. It has a compression ratio designed to take advantage of the 130 octane number of natural gas (ENGVA, 2006). Dedicated NGV has been designed to consider the combustion characteristics of the fuel so this engine is friendly to the environment (ENGVA, 2006). Nissan Diesel Motor Co, Ltd developed a CNG engine for heavy-duty garbage trucks by modifying a 12.503 liter intercooled and turbocharged in-line 6 cylinder heavy duty diesel engine (Hikiri *et al.*, 2000). The full-load performance of the developed engine was compared with the diesel engine and the CNG engine for heavy-duty buses. The developed engine was improved significantly in power and torque in comparison with the CNG engine for buses (Hikiri *et al.*, 2000).

In this research, both technologies were economically compared in terms of the supply side and demand side investment costs in order to determine the suitable technology for promotion in Thailand. In addition, the environment perspectives from NGV emissions composed with carbon dioxide (CO_2), hydrocarbon (HC), nitrogen oxide (NO_x), carbon monoxide (CO) and particulate matter (PM) were studied.

2. Methodology

2.1 Analysis of natural gas vehicle program in Thailand

The economic aspect of Thailand natural gas vehicle both dedicated retrofit and diesel dual fuel was investigated in terms of the cost of diesel oil that can be substituted for by natural gas in the case of pickup truck, non-fixed route truck and private truck vehicles. In mid 2007 Thailand had 145 natural gas fueling stations (PTT, 2007). The details of these 145 natural gas fueling stations i.e. types, number of refueling stations, investment cost include operating cost are shown in Table 1, while the amount of fuel services in each type of refueling stations and total amount of fuel services from 145 refueling stations are shown in Table 2.

2.2 Projection of economic aspect for Thailand natural gas vehicle

The economic assessments for applying natural gas as fuel in diesel vehicles were investigated involved with

Table 1. Types of refueling stations, investment cost and maintenance cost from 65 refueling stations

Type	Number	Refueling investment cost (Million baht)	Operating cost (Million baht/year)
Conventional	24	3,000	13.44
Mother	11	1,969	49.50
Daughter	110	1,650	38.50
Total	145	6,619	101.44

Table 2. Total amount of fuel services per day

Type	Number	Amount of refuel services (ton/day)	Total amount of refuel services (ton/day)	Total amount of refuel services (kilograms/day)	Equivalent oil services (barrel/day)
Conventional	24	30			
Mother	11	30	1,380	1,380,000	7,841
Daughter	110	3			

Assumption: Natural gas 1.1 kilogram equal to 1 liter diesel, 1 barrel = 160 liter supply side and demand side investment costs following PTT Public Company Limited plan on NGV expansion during 2006 to 2011. Table 3 and Table 4 show target expansion of refueling station and NGV following PTT target plan (PTT, 2007). The expansions of dedicated retrofit truck, dual fuel truck and dual fuel pickup truck vehicles are shown in Table 5 (PTT, 2007).

The information of PTT Public Company Limited on the conversion cost of diesel dual fuel and dedicated retrofit are shown in Table 6 (PTT, 2007), while the average distance traveling of vehicles used in this research is given in Table 7 (Pongthanaisawan *et al.*, 2006). Fuel economy is divided into average fuel economy in Bangkok area (liter/vehicle-100 kilometer) and average fuel economy in provincial area (liter/vehicle-100 kilometer) as shown in Table 8 (Pongthanaisawan *et al.*, 2006).

2.3 Analysis of environmental perspective of Thailand natural gas vehicle

Following PTT Public Company limited plan on NGV expansion during year 2006-2010, the future environmental benefits of Thailand natural gas vehicle was studied. The Pollution Control Department (PCD), Government of Thailand, reported the emissions tests of diesel vehicles, diesel dual fuel and natural gas vehicles, both light-duty diesel vehicles and heavy-duty diesel vehicles, as shown in Table 9 (PCD, 2007). The comparison of engine emission between light-duty diesel vehicle with light-duty diesel dual fuel and light-duty dedicated is given in Table 10 and Table 11, whereas Table 12 shows the comparison of engine emission between heavy-duty dedicated and heavy-duty diesel vehicle.

3. Results

3.1 Analysis of possible reducing of diesel oil import rate by NGV

In July 2007, Thailand had natural gas vehicle of 38,351 units divided into gasoline substitute, 34,306 units, and diesel substitute, 4,045 units (PTT, 2007). Therefore the ratio of gasoline/diesel substitute by NGV is about 8.5/1.0. From our 145 refueling stations, the total amount of fuel services is 1,380 ton/day (1,380,000 kg/day), which can substitute oil to the amount of 7,841 barrels/day. By applying the ratio of gasoline/diesel utilization, CNG can substitute gasoline at about 7,016 barrel/day and diesel at about 825 barrel/day.

Currently, Thailand import rate of crude oil for applying in the transportation sector is approximately 824,000 barrel per day (DEB, 2007). This crude oil theoretically is separated into gasoline and diesel with the constant ratio of 0.6 to 0.4 by the normal refinery process. Therefore, the amounts of gasoline and diesel productions per day are 494,400 barrel/day and 329,600 barrel/day respectively. It is identified that Thailand has some amount of excess gasoline

Table 3. Target refueling station expansion of PTT Public Company Limited during year 2006 to 2011

Part	2006	2007	2008	2009	2010	2011
Bangkok/surrounding/Central	73	181	212	253	277	285
Provincial	31	89	138	172	203	250
Fueling station (Accumulate)	104	270	350	425	480	535

Table 4. Target expansion natural gas vehicles

(Car: Unit)

Types	2006	2007	2008	2009	2010	2011
Gasoline	22,890	52,000	74,700	101,000	128,000	160,000
Diesel	2,950	8,850	24,300	50,300	79,600	96,600
NGV (Accumulate)	25,840	60,850	99,000	151,300	207,600	256,600

Table 5. PTT target expansion diesel natural gas vehicle

(Accumulate :Unit)

Diesel	2006	2007	2008	2009	2010	2011
Dedicated retrofit truck	150	1,000	7,000	20,000	35,000	45,000
Dual fuel truck	630	2,000	7,000	15,000	25,000	30,000
Dual fuel pickup	1,700	2,000	2,500	3,500	4,500	5,000

Table 6. Average investment cost of dedicated retrofit and DDF

Type	Average conversion cost (Baht/Unit)
4 wheel pickup truck (dual fuel)	45,000
6 wheel non-fixed route truck (dual fuel)	77,500
10 wheel private truck (dual fuel)	110,000
6 wheel non-fixed route truck (dedicated retrofit)	450,000
10 wheel private truck (dedicated retrofit)	600,000

Table 7. Average distance traveling of vehicles

Vehicle Type	Average Vehicle Kilometer Traveling (km/year)		
	Bangkok area	Provincial area	Average
Pickup truck	17,289	17,289	17,289
Non-fixed route truck	31,102	65,242	48,172
Private truck	29,608	57,022	43,315

Table 8. Fuel economy of vehicle by fuel types

Vehicle Type	Average Fuel Economy (liter/vehicle-100 kilometer)							
	Bangkok area				Provincial area			
	Gasoline	Diesel	LPG	CNG	Gasoline	Diesel	LPG	CNG
Pickup	8.0515	7.3260	9.7264	8.7761	8.7413	8.2305	10.0000	-
Non-fixed route truck	-	10.8696	-	11.1073	-	10.8696	-	-
Private truck	-	12.5628	-	12.8375	-	12.5628	-	-

Table 9. Summary of diesel vehicles and natural gas vehicles emission tests performed by PCD's laboratory

Sample	Type	Piston engine capacity (cc)	Fuel	CO_2 (g/km)	HC (g/km)	NO_x (g/km)	CO (g/km)	PM (g/km)	Efficiency (km/liter)
1	LD	3,000	Diesel	204.575	0.019	0.847	0.216	0.031	8.91
			Diesel + CNG	205.382	1.556	0.785	1.253	0.027	8.22
2	LG	1,497	Gasoline 91	148.152	0.034	0.198	1.571	-	10.35
			LPG	126.886	0.022	0.059	0.427	-	9.10
3	LD	2,446	Diesel	221.767	0.045	0.606	0.409	0.035	11.93
			CNG	268.883	0.175	0.185	1.175	0.006	6.61
4	LG	1,769	Gasohol 95	176.610	0.012	1.604	0.047	-	14.25
			CNG	153.041	0.347	1.331	0.016	-	15.68
5	HD	11,967	Diesel	1510.95	10.39	48.29	24.97	1.83	3.39
6	HD	11,967	CNG	1283.46	7.34	36.91	10.39	1.10	2.40

Remark: LD = Light Duty Diesel Vehicle, LG = Light Duty Gasoline Vehicle,
HD = Heavy Duty Diesel Vehicle, CNG = Compressed Natural Gas

Table 10. Engine emissions of light-duty diesel dual fuel when compare with light-duty diesel vehicle emissions (g/km)

Type	CO_2	HC	NO_x	CO	PM
Light-duty diesel dual fuel	↑ 0.40%	↑ 98%	↓ 7%	↑ 82%	↓ 13%

Table 11. Engine emissions of light-duty dedicated when compare with light-duty diesel vehicle emissions (g/km)

Type	CO_2	HC	NO_x	CO	PM
Light-duty dedicated	↑ 17%	↑ 74%	↓ 69%	↑ 65%	↓ 82%

Remark: ↑ Increase, ↓ Decrease

Table 12. Engine emissions of heavy-duty diesel when compare with heavy-duty dedicated emissions (g/km)

Type	CO_2	HC	NO_x	CO	PM
Heavy-duty dedicated	↓ 15%	↓ 29%	↓ 23%	↓ 58%	↓ 39%

for exporting. As the diesel substitute by natural gas increases, Thailand can reduce crude oil import but export a lower amount of gasoline. Figure 1 shows the relation between natural gas vehicle ratio (diesel/gasoline) and imported crude oil. The result of the relation between crude oil import and natural gas vehicle ratio (diesel/diesel + gasoline) as shown in the figure indicates that natural gas vehicle ratio has great potential benefit to reduce crude oil import and no impact in the part of gasoline consumption.

3.2 Economic aspect of natural gas vehicle for diesel engines

The study of economic aspect is based on the following assumptions:

- Refueling station equipment life is 30 years without sink cost
- Conversion kit life is 10 years without sink cost
- Interest rate investment cost of refueling station is 3%
- Interest rate investment cost of conversion cost is 7%
- Monetary inflation rate is 2%
- The types of vehicle focused on this research are pickup truck, non-fixed route truck and private truck vehicles.

The economic analysis in order to use natural gas as

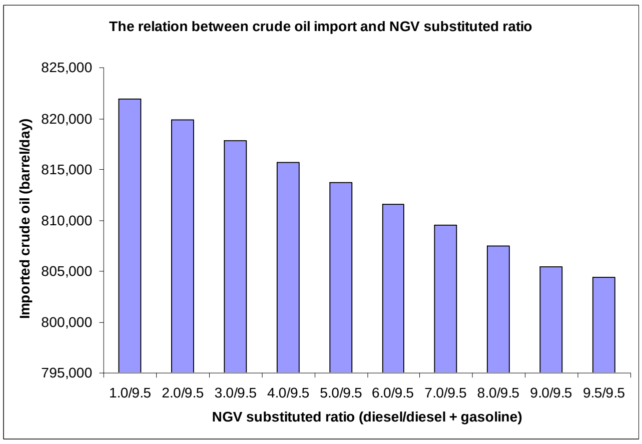

Figure 1. Crude oil import and NGV substituted ratio

fuel in diesel vehicles following PTT target plan during 2006 to 2011 is divided into supply side and demand side. The investment costs are shown in equation (1) and (2), while the total cost can be obtained from equation (3).

Supply side investment cost =
Refueling station investment cost + Operating cost (1)

Demand side investment cost =
Conversion cost + Maintenance cost (2)

Total costs =
Supply side investment cost + Demand side investment cost (3)

The total costs can invest in term of annual worth. A series of annual worth is shown in equation (4) (Rijiravanich and Ploymeeca, 1998)

$$A = P\left[\frac{i(1+i)^n}{(1+i)^n - 1}\right] \quad (4)$$

when: A = annual worth
P = present worth
i = interest rate in %
n = project life in years

The total costs that invest in each year must be considering monetary inflation rate. The inflation rate is shown in equation (5) (Thuesen, 2001)

$$F = P\left(1 + \frac{f}{100}\right) \quad (5)$$

when: F = future sum
P = present worth
f = inflation rate in %

The cost of diesel oil substituted by natural gas is given in the equation (6):

Cost of diesel oil substitute =
Average fuel economy/year × Diesel price (6)

The results of the studies are shown in Figure 2, Figure 3 and Figure 4. The results indicated that the dedicated retrofit has investment costs higher than dual fuel, but can achieve higher diesel saving than dual fuel. The payback period for user is presented in Table 13. The results indicate

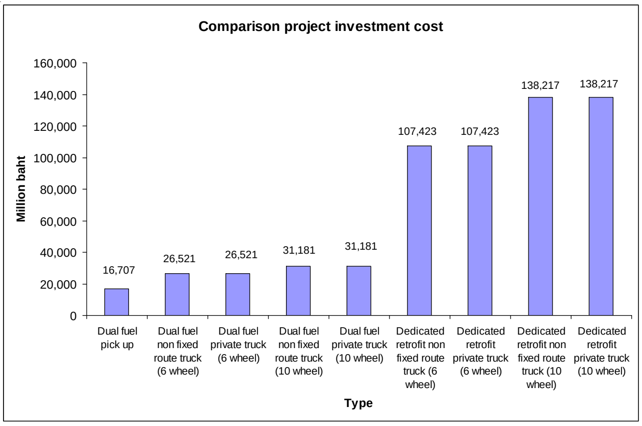

Figure 2. Comparison equity annual project payment of dual fuel and dedicated retrofit

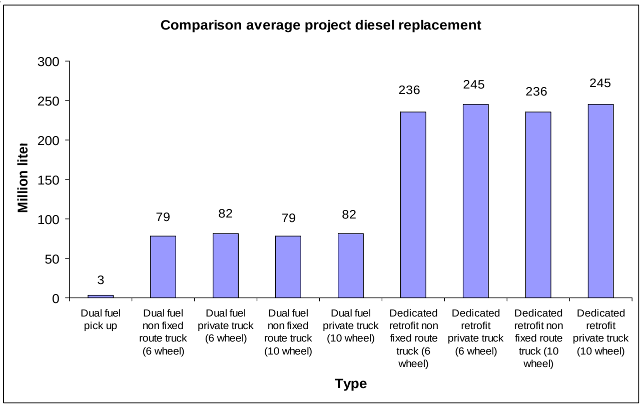

Figure 3. Average project diesel replacements between dual fuel and dedicated retrofit

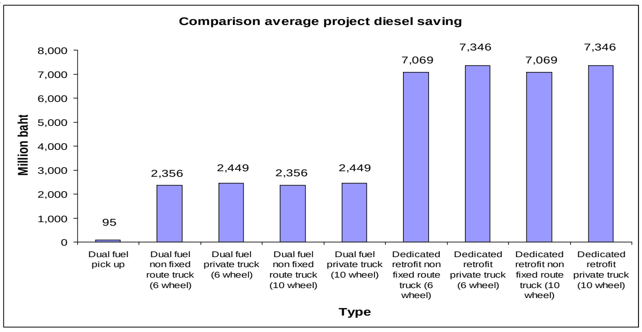

Figure 4. Average diesel saving between dual fuel and dedicated retrofit

Table 13. Summary payback period of user

Type	% Natural gas : Diesel (Year)		Dedicated retrofit (Year)
	40 : 60	50 : 50	
Dual fuel pickup	4	3	
Dual fuel non-fixed route truck (6 wheel)	2	2	
Dual fuel private truck (6 Wheel)	2	2	
Dedicated retrofit non-fixed route truck (6 wheel)			4
Dedicated retrofit private truck (6 wheel)			4
Dual fuel non-fixed route truck (10 wheel)	3	2	
Dual fuel private truck (10 Wheel)	2	2	
Dedicated retrofit non-fixed route truck (10 wheel)			5
Dedicated retrofit private truck (10 wheel)			5

that when natural gas replacement of diesel oil increases from 40% to 50%, it provides a great benefit for the payback period of user particularly in the case of dual fuel pick up truck. The results also indicate that the payback period of dual fuel for non-fixed route truck is identical to that of dual fuel for private truck (in the case of both 6 and 10 wheel). The payback period of dedicated retrofit for non-fixed route truck and private truck are approximately similar for both 6 and 10 wheel and obtain longer payback period than dual fuel due to its higher conversion costs.

3.3 Analysis environmental benefits from the use of natural gas vehicle

The main emission considered in this study is carbon dioxide (CO_2), the main course of global warming. The results of the study are shown in Figure 5, Figure 6 and Figure 7. The results demonstrate that in the case of light duty diesel, dedicated retrofit emitted higher levels of CO_2 than both dual fuel and conventional diesel because of engine efficiency including engine fine tuning and conversion technologies, whereas the CO_2 level from conventional diesel and dual fuel are always identical. For heavy duty, dedicated retrofit emitted a lower level of CO_2 than normal diesel. Other emissions from engine were studied i.e. hydrocarbon (HC), nitric oxide (NO_x), carbon monoxide (CO) and particulate matter (PM) and the results are shown in Tables 14-16. The results demonstrate that in the case of light duty diesel, dedicated retrofit engine emits higher levels of HC and CO than diesel engine; in contrast, it emits lower levels of NO_x and PM than diesel and dual fuel. Dual fuel emits

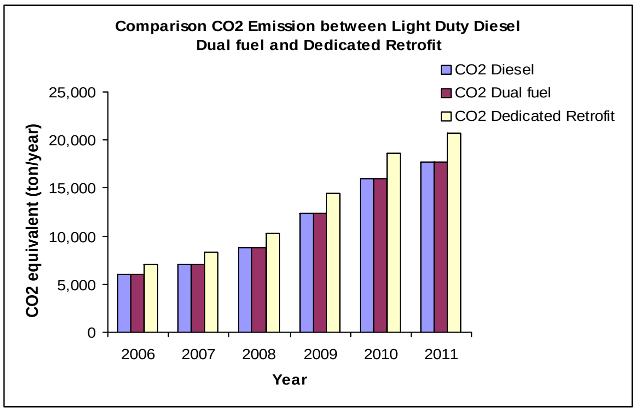

Figure 5. Comparison CO_2 emission between light duty diesel dual fuel and dedicated retrofit

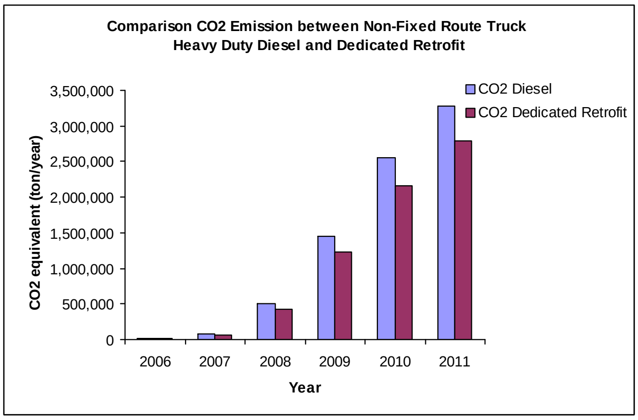

Figure 6. Comparison CO_2 emission of non-fixed route truck heavy duty diesel and dedicated retrofit

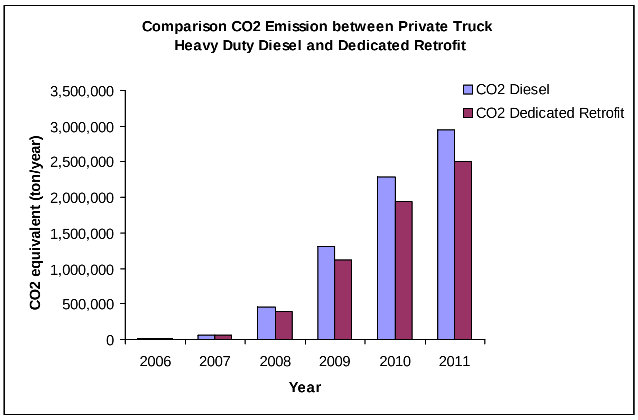

Figure 7. Comparison CO_2 emission of private truck heavy duty diesel and dedicated retrofit

higher HC and CO than diesel and dedicated retrofit but emits lower levels of NO_x and PM than diesel. In addition, for heavy duty diesel, it was demonstrated that non-fixed route truck and private truck heavy duty dedicated retrofit have potential to reduce emissions of HC, NO_x, CO and PM when

Table 14. Comparison light duty emissions (diesel base)

Types of emissions	Light duty vehicle emissions (ton/year)		
	Dedicated	Diesel	Dual fuel
Hydrocarbon (HC)	2.86	1.64	3.25
Nitrogen oxide (NO_x)	22.70	73.22	68.10
Carbon monoxide (CO)	30.81	18.67	33.98
Particulate matter (PM)	0.48	2.68	2.33

Table 15. Comparison non-fixed route truck heavy duty emissions (diesel base)

Types of emissions	Non fixed route truck heavy duty emissions (ton/year)	
	Dedicated	Diesel
Hydrocarbon (HC)	15,991	22,523
Nitrogen oxide (NO_x)	80,604	104,680
Carbon monoxide (CO)	22,734	54,128
Particulate matter (PM)	2,420	3,967

Table 16. Comparison private truck heavy duty emissions (diesel base)

Types of emissions	Private truck heavy duty emissions (ton/year)	
	Dedicated	Diesel
Hydrocarbon (HC)	14,379	20,252
Nitrogen oxide (NO_x)	72,477	94,126
Carbon monoxide (CO)	20,442	48,671
Particulate matter (PM)	2,176	3,567

compared to normal heavy duty diesel. The other emission characteristics are caused by engine efficiency, engine fine tuning and conversion technologies and also the lack of a legal natural gas standard in Thailand.

4. Conclusion

The analysis of Thailand natural gas vehicle program between crude oil import and natural gas vehicle ratio (diesel/ diesel + gasoline) indicates that natural gas vehicle ratio has potential benefit in order to reduce crude oil import and less impact in the part of gasoline consumption. The economic assessments of Thailand natural gas vehicle program in the future during 2006 to 2011 indicate that dedicated retrofit has higher investment costs than dual fuel, but can achieve higher diesel saving than dual fuel. The payback period for NGV user in the case of dual fuel is shorter than that of dedicated retrofit.

The green house gas (carbon dioxide, CO_2) is the main cause of global warming emitted from light duty dedicated retrofit NGV higher than in the case of both dual fuel and conventional diesel while CO_2 level emitted from conventional diesel and conventional diesel and dual fuel are always identical. In the case of heavy duty diesel, dedicated retrofit emitted lower level of CO_2 than normal diesel. Other emissions from engine, in the case of light duty diesel, dedicated engine emitted higher levels of HC and CO than conventional diesel; in contrast, it emitted lower levels of NO_x and PM than conventional diesel and dual fuel.

Dual fuel emitted higher levels of HC and CO than diesel and dedicated but emitted lower levels of NO_x and PM than diesel. In addition, for heavy duty these demonstrated that non-fixed route truck and private truck heavy duty dedicated have potential in order to reduce emissions of HC, NO_x, CO and PM when compared to normal heavy duty diesel.

The efficiencies under dual fuel and dedicated retrofit operation were lower than those of a normal diesel engine.

Acknowledgement

The financial support from The Joint Graduate School of Energy and Environment King Mongkut's University of Technology Thonburi and Chulalongkorn University Energy Research Institute throughout this project is gratefully acknowledged.

References

Energy Policy and Planning Office. Energy Demand Outlook. 2006-2020. Available online : http://www.jgsee.kmutt.ac.th/new/announcement/pdf (November 15, 2005)

European Natural Gas Vehicle Association. Dual Fuel (Natural Gas/Diesel) Engines: Operation, Applications & Contribution. Available online: http://www.unece.org /trans/ doc/2001/wp29grpe/TRANS-WP29-GRPE-42-inf18.pdf (November 3, 2006)

Papagainnakis, R.G. and Hountalas, D.T. 2004. Combustion and exhaust emission characteristics of a dual fuel compression ignition engine operated with pilot Diesel fuel and natural gas. Energy Conversion and Management., 45 : 2971-2987.

Hikiri, K., Nakamura, A., Harayama, N. and Sasaki, M. 2000. Development of the High-power CNG Engine for Heavy-duty Garbage Trucks. International Association for Natural Gas Vehicles, NGV 2000 Yokohama Japan. 507-516

PTT Public Company Limited. Thailand NGV Statistic. Available online: http://www.pttplc.com/th/document/ pdf/ngv/Static_NGV.pdf (December 13, 2007)

PTT Public Company Limited. NGV Policy and Roadmap. Available online: http://www.pttplc.com/th/document/ pdf/ngv/ga_ng_04_03-01.pdf (March 28, 2007)

PTT Public Company Limited. Natural Gas for Vehicle. Available online: http:// www.pttplc.com/th/ptt_core.asp?page=ps_pr_fu_ga_ng_02_01 (March 9, 2007)

Pongthanaisawan, J., Sorapipatana, C. and Limmeechokchai, B. 2006. Land Transport Demand Analysis and Energy Saving Potentials in Thailand. Sustainable Energy and Environment, 2006 Bangkok Thailand 1096-1102

Pollution Control Department (PCD), Government of Thailand. Emission tests of Natural Gas Vehicle. (January 30, 2007)

Department of Energy Business. Amount of crude oil import. Available online: http://www.doeb.go.th/information/stat/imp-exp50.ppt. (September 15, 2007)

Rijiravanich, V. and Ploymeeca, C. 1998. Engineering Economy, 5th Ed, 147-157. Chulalongkorn University Press, Bangkok.

Thuesen, G.J. 2001. Engineering Economy, 9th Ed, 124-128. Prentice-Hall International, Inc. New Jersey.