Life-Cycle Assessment of Conventional and Alternative Fuels for Road Vehicles

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ABSTRACT

Results of the life-cycle assessment (LCA) of several conventional and alternative motor vehicle fuels are discussed. The analysis was accomplished using the composite program EDIP-GREET, which is based on the Danish EDIP impact assessment and the American GREET 1.5a fuel-cycle models. The options evaluated included conventional fuels (gasoline and diesel), biofuels (bioethanol and biodiesel) and natural gas derivatives (LNG, CNG and methanol), with the analysis being limited to air pollution and resource depletion impacts. Sensitivity analysis was also used to determine the effect of electrical power generation mix on total environmental impacts. The model outputs indicate no significant over-all benefits resulting from the substitution of natural gas-based fuels for gasoline. On the other hand, the use of bioethanol and biodiesel in place of gasoline and diesel, respectively, is expected to yield significant gains particularly with respect to greenhouse gas emissions and fossil fuel depletion.

Keywords: Life-cycle assessment (LCA), alternative fuels

Introduction

Automotive transport is a major contributor to local and global air pollution as well as fossil fuel resource depletion. In the Philippines, for example, road vehicles accounted for 13% of the country's primary energy consumption in the late 1990s, as well as a proportionate share of the estimated 63×10^6 ton per annum national CO_2 emission inventory (World Resources Institute, 2000). Alternative propulsion systems are considered to be the most promising long-term solution to the environmental impacts resulting from road vehicle use (Poulton, 1994). For the Philippines in particular, there is significant potential for the use of biofuels and natural gas derivatives as petroleum substitutes for vehicles with spark ignition (SI) and compression ignition (CI) engines.

In the aftermath of the oil shocks of the 1970s, the Philippines explored liquid biofuels as a means of insulating her economy from volatile petroleum prices. One of the fuels identified for development was bioethanol derived for sugarcane, which was used in gasoline blends called alcogas (Lorilla, 1982; Del Rosario et al., 1985). The other fuel was biodiesel derived from coconut oil, or cocodiesel. The alcogas and cocodiesel programs were also meant to provide alternative markets to revitalize the country's sugar and coconut agricultural sectors (Eala, 1985). Both biofuel programs were abandoned in the mid-1980s due in part to domestic political turmoil, and in part to stable World oil prices. Today biofuels merit reconsideration, but for environmental rather than economic considerations.

The development of the commercially viable Camago-Malampaya natural gas (NG) deposits in the western Philippines has stimulated interest in the utilization of this relatively clean-burning fuel for various applications. Although near-term plans focus on the use of NG for power generation, other applications will also be explored in the long run. There is particular interest in using NG as an environment-friendly alternative transportation fuel (Philippine Department of Energy, 2000). NG can be used directly in liquefied (LNG) or compressed form (CNG) in vehicles with modified. Alternatively, it can be converted to methanol, which requires significantly less engine modification.

Life-Cycle Assessment

Life-cycle assessment (LCA) is a conceptual framework and methodology for the assessment of environmental impacts of product systems on a cradle-to-grave basis. The LCA approach is a departure from conventional assessments which tend to focus either on product manufacturing or end-of-life disposal. Analysis of a system under LCA encompasses the extraction of raw materials and energy reseources from the environment, the conversion of these resources into the desired product, the utilization of the product by the consumer, and finally the disposal, reuse, or recycle of the product after its service life. The LCA approach is an effective way to introduce environmental considerations in process and product design or selection (Azapagic, 1999).

Modern LCA methodology is based on standards developed in the 1990s by the Society of Environmental Toxicology and Chemistry (1991) and the International Organisation for Standardisation (ISO, 1997; 1998; 2000a;

2000b). The latter's LCA standards are known as the ISO 14040 series and fall under the general framework of the ISO 14000 environmental management standards.

LCA consists of four components:

- *Goal and Scope Definition* – specifies the objective of the assessment as well as the assumptions under which all subsequent analysis is done. Under the SETAC framework, also specifies conditions for subsequent sensitivity and scenario analysis.
- *Inventory Analysis* – involves the quantification of environmentally relevant material and energy flows of a system using various sources of data.
- *Impact Assessment* – analyzes and compares the environmental burdens associated with the material and energy flows determined in the previous phase through classification, normalization, and weighting.
- *Improvement Analysis* (SETAC, 1991) or *Interpretation* (ISO, 1997; 2000) – utilizes the results of the preceding stages to generate a decision or plan of action. Under the ISO framework, this component also includes sensitivity analysis.

Objective

This purpose of this study was to assess the environmental impacts of biofuels (bioethanol and biodiesel) and natural gas derivatives (LNG, CNG and methanol) relative to conventional automotive fuels (gasoline and diesel), taking into account life-cycle considerations, in order to identify the best environmental option.

Model Description

The components of the EDIP-GREET LCA model are:

- *The GREET fuel-cycle inventory submodel*. The GREET (Greenhouse Gases, Regulated Emissions and Energy Use in Transportation) model was developed by Argonne National Laboratory in the mid-1990s for the United States Department of Energy (Wang, 1996). This public-domain model can be downloaded from the Argonne website (www.transportation.anl.gov). GREET version 1.5a (Wang, 1999) was used as the inventory submodel of EDIP-GREET. It is coded in Microsoft Excel and Visual Basic, and its modular structure allows users to create new fuel pathways or modify existing ones. The most recent version of this model is GREET 1.6, which is enhanced with graphic user interfaces (GUIs) and Monte Carlo simulation capability (Wang, 2001). GREET simulations are limited to the following environmental flows: greenouse gas emissions (CO_2, CH_4 and N_2O); miscellaneous air emissions (VOC, CO, NO_x, PM_{10} and SO_x); and energy usage (total, fossil and petroleum energy).

- *The EDIP impact assessment submodel*. The EDIP (Environmental Design of Industrial Products) method was developed in the mid-1990s by a consortium that included the Technological University of Denmark, the Confederation of Danish Industries, the Danish Environmental Protection Agency and private-sector partners. The impact assessment procedure specified under the EDIP framework relies on classification under predefined environmental impact categories, characterization using equivalency factors, and normalization with weighting using the concept of the person-equivalent (Hauschild and Wenzel, 1997; Wenzel et al, 1997). In this study the EDIP impact assessment method was coded onto the GREET 1.5a spreadsheet to allow comprehensive analysis based on environmental impact themes (rather than just inventory flows) to be performed. Only eight impact categories are applicable to the inventory outputs of the GREET submodel: global warming (GWP), acidification (AP), photochemical ozone formation (POFP), nutrification (NP), human toxicity via inhalation (HTP), and resource depletion (RDP) of oil, coal and natural gas.

Description of Fuel Life Cycles

The fuel life cycles simulated in this study were:

- Bioethanol – assumed to be produced from cellulosic agricultural waste using enzymatic hydrolysis and fermentation (Wang, 1999).
- Biodiesel – assumed to be coconut oil methyl ester (COME), which is produced by transesterification of coconut oil with methanol derived from NG (Tan et al., 2002).
- Liquefied Natural Gas (LNG) – assumed to be liquefied in centralized processing facilities and subsequently transported in cryogenic tanks to refueling sites.

- Compressed Natural Gas (CNG) – assumed to be distributed by pipeline to refueling sites and compressed prior to sale.
- Methanol – assumed to be produced from NG through steam methane reforming (Wang, 1999).

Simulation Parameters and Assumptions

In this study the following principal modifications were made in the GREET and EDIP submodels:

- Assessments are normalized on a per vehicle-km basis.
- Three different electricity generation scenarios were used for the marginal power requirements of the fuel life cycles. Scenario A was based on the Philippine Department of Energy (2000) projections for the year 2009. Scenarios B and C assumed that the marginal power demand was supplied using natural gas and renewables (e.g., solar or wind energy), respectively. The three scenarios are summarized in Table 1.

Table 1 Marginal Power Generation Scenarios

	Power Mix Scenario		
	A	B	C
Coal	45%	0%	0%
Oil	10%	0%	0%
Natural Gas	16%	100%	0%
Others	29%	0%	100%

- The natural gas specifications shown in Table 2 were used in place of the default properties embedded in GREET 1.5a. These are based on the properties of Camago-Malampaya natural gas (Philippine DOE, 2000).

Table 2 Properties of Camago-Malampaya Natural Gas

Property	Specification
Net Heating Value	46 MJ/kg
Carbon Emission Factor	0.054 kg CO_2/MJ
Sulfur Emission Factor	0

- Fuel economy assumptions for vehicles are conservative. Vehicles powered by bioethanol, LNG, CNG and methanol are assumed to be similar in efficiency to gasoline-powered units. Diesel and biodiesel are also assumed to give identical fuel economies.

- The sulfur content of diesel was assumed to be .05% or 500 ppm by weight, based on the long-term targets specified by the guidelines of the Philippine Clean Air Act (Philippine DENR, 2000). The default value in GREET 1.5a is .025% or 250 ppm.
- Human toxicity potential of PM_{10} emissions was assumed to be 6.7×10^3 m^3/g, based on the ambient concentration limit of 150 $\mu g/m^3$ specified in the implementing guidelines of the Philippine Clean Air Act (Philippine DENR, 2000). No default value is specified in the EDIP model.
- In this study the EDIP human toxicity potential of toluene (2.5×10^3 m^3/g) was used as a representative value for mixed volatile organic compounds (VOCs).

Results and Discussion

Environmental impacts associated with air emissions and fossil fuel usage for Power Scenario A are shown in Figures 1 and 2, respectively. Total impacts for bioethanol and biodiesel are significantly lower than those of gasoline and diesel, primarily due to sharp reductions in CO_2 emissions (and GWP) and fossil fuel consumption. Impacts of the two biofuels in other impact categories remain roughly comparable to those of conventional fuels. Cumulative air emission impacts from CNG and methanol are slightly lower than those of gasoline. LNG is actually the worst environmental option of the seven fuels evaluated. In general, all three NG derivatives produce more total impacts than diesel. As might be expected, the depletion impacts of LNG, CNG and methanol are skewed towards NG resource consumption.

Air emission impacts and fossil fuel depletion scores for Power Scenario B are shown in Figures 3 and 4, respectively. Corresponding data for Power Scenario C are given in Figures 5 and 6. These two scenarios represent progressively cleaner grid electricity. In general, the impacts of the liquid fuels show little sensitivity to power mix. However, the environmental impacts LNG and CNG improve slightly relative to the other five fuels as electricity generation becomes cleaner. This is attributable to the fact that significant electrical inputs are required for NG liquefaction, pipeline transmission and compression; reduction in impacts per kW-h of electricity also translate to reduced impacts for these two fuel cycles. Total resource depletion impacts for Power Scenario C are also lower than those from the previous two scenarios because of the use of renewable energy for power generation.

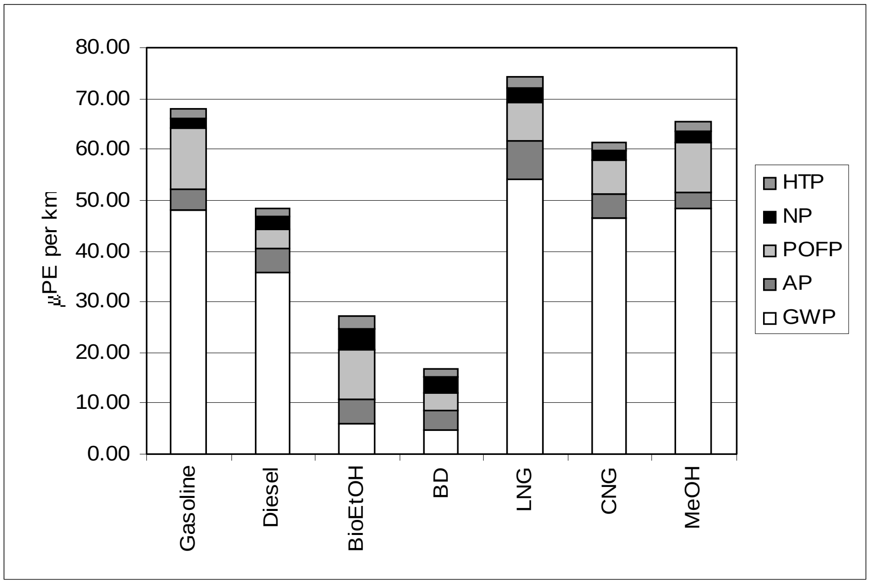

Figure 1 Air Emission Impacts of Alternative Fuels (Power Scenario A)

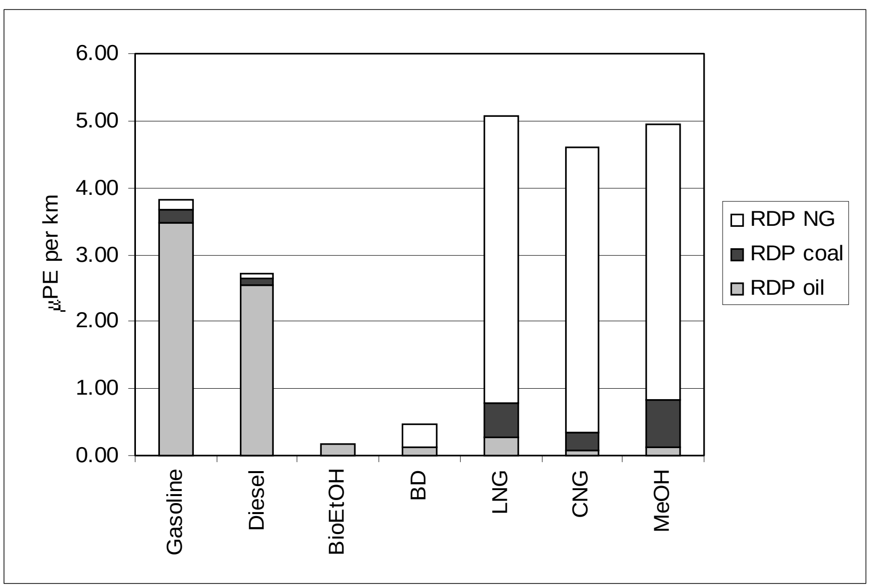

Figure 2 Resource Depletion Impacts of Alternative Fuels (Power Scenario A)

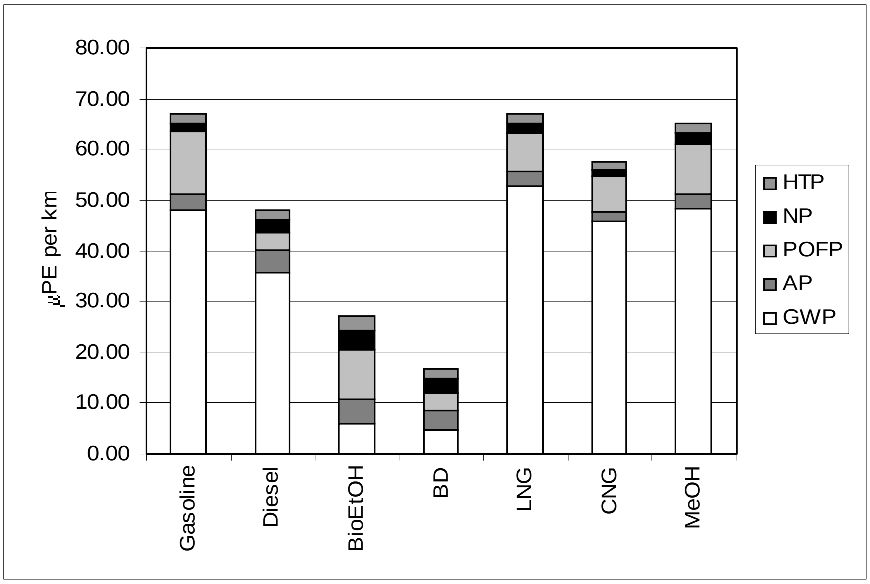

Figure 3 Air Emission Impacts of Alternative Fuels (Power Scenario B)

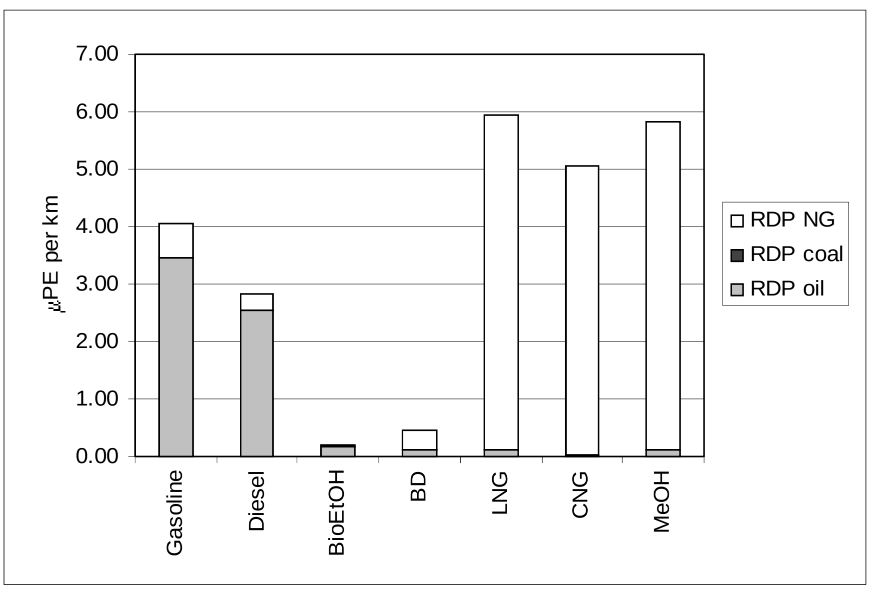

Figure 4 Resource Depletion Impacts of Alternative Fuels (Power Scenario B)

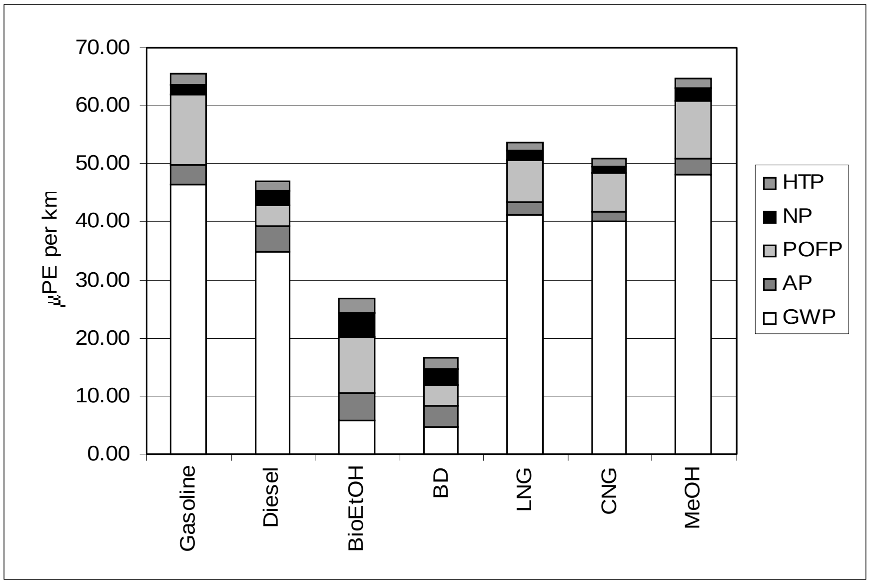

Figure 5 Air Emissions Impacts of Alternative Fuels (Power Scenario C)

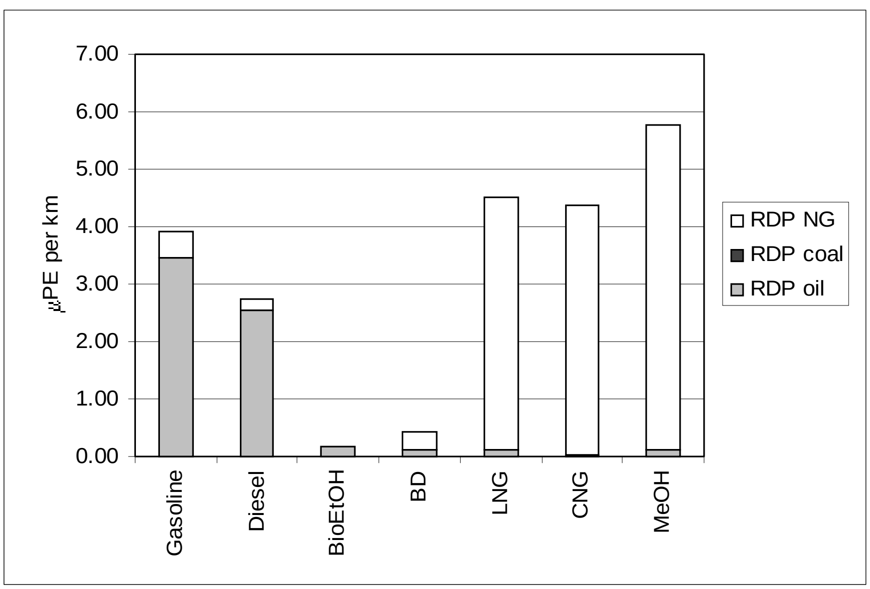

Figure 6 Resource Depletion Impacts of Alternative Fuels (Power Scenario C)

Conclusions

Based on the specified assumptions, the results of this study indicate little or no environmental benefit from the use of NG as an automotive fuel. Of the three options available for NG utilization, the environmentally optimal alternative is CNG. In terms of total environmental impact, the methanol conversion pathway gives only marginal improvements relative to gasoline, while LNG fails to yield any gains at all. The biofuel options, bioethanol and biodiesel, yield benefits primarily with respect to global warming and fossil fuel resource depletion; impacts in other categories are roughly comparable to those of conventional fuels.

These findings imply that alternative-fueled vehicles must be optimized to take advantage of specific fuel properties in order for potential environmental benefits to be realized; mere conversion of existing vehicle engines will most likely result in mediocre emissions reduction. For example, bioethanol, LNG, CNG and methanol have high octane ratings that allow for higher compression ratios. Engines designed specifically for these fuels can take advantage of their anti-knock properties. They will have higher thermal efficiencies, resulting in improved fuel economy and reduced emissions on a per km basis.

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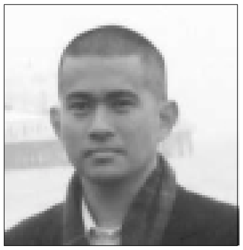

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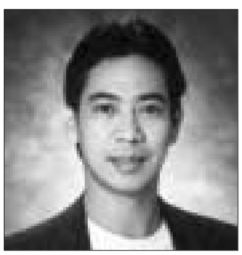

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