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# Life cycle assessment of LPG and diesel vehicles in Korea

**Min June Kim*,‡, Eun Jun Lee*,‡, Chul-Jin Kim**, Ung Gi Hong**, Deuk Soo Park**, Haebin Shin**, and Kwan-Young Lee*,***,****,†**

*Department of Chemical and Biological Engineering, Korea University, 145 Anam-ro, Seongbuk-gu, Seoul 02841, Korea
**SK Gas, ECO Hub, 332 Pangyo-ro, Bundang-gu, Seongnam-si, Gyeonggi-do 13493, Korea
***Super Ultra Low Energy and Emission Vehicle (SULEEV) Center, Korea University, 145 Anam-ro, Seongbuk-gu, Seoul 02841, Korea
****Graduate School of Energy and Environment (KU-KIST Green School), Korea University, Seoul 02841, Korea
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**Abstract**−With LPG automobile deregulation in 2019, the demand for LPG automobiles has increased in Korea; therefore, a comparison of the eco-friendliness of LPG and other petroleum-based vehicles has become necessary. We conducted a well-to-wheels (WTW) analysis of diesel and LPG fuel in Korea. GREET, PRELIM, and GHGenius models were utilized to calculate and appropriately allocate the energy use and greenhouse gas (GHG) emission in the life cycle process of diesel and LPG fuel. In the well-to-tank (WTT) step, the GHG emissions of LPG were lower than that of diesel because of the lower energy consumption of LPG in fuel production. For the WTW comparison, we selected four automobiles currently sold in Korea and a 1,500 kg curb weight model. The WTW GHG emissions of the LPG automobiles were lower than those of the diesel SUV and the 1 ton truck. On the other hand, the WTW GHG emissions of diesel automobiles were lower in the sedans and in the 1,500 kg model. Finally, it was verified that LPG automobiles were advantageous in terms of GHG emission in the SUV and one-ton truck, although the GHG emissions of diesel and LPG vehicles can vary depending on the fuel economy of the vehicles.

Keywords: Life Cycle Assessment, Well-to-wheel Analysis, Greenhouse Gas Emission, Diesel and LPG Vehicles

## INTRODUCTION

As the amount of GHG increases worldwide and global warming accelerates, global discussions are being conducted to reduce GHG. Since the adoption of the Paris Agreement at the Climate Change Convention in Paris (2015), GHG reduction has become a global regulatory target. Providing direction for GHG reduction until 2020, the Paris Agreement aims to maintain a temperature rise of less than 2 °C and possibly less than 1.5 °C above levels in the pre-industrial era [1]. Accordingly, going forward, it is necessary to reduce GHG emissions in all industries. The transportation sector accounted for 29.1% of all U.S. GHG emissions in 2017 [2], and the vehicle sector accounted for 71.8% of the GHG emissions of the transportation sector [3]. Accordingly, major industrial countries are continually tightening regulations on vehicle $CO_2$ emissions, and the Obama administration introduced a policy to force vehicle fuel economy to increase to approximately 54.5 mpg or more by 2025 [4].

Therefore, a comparative analysis of the eco-friendliness of various vehicle types and policy establishment has become important, as the global interest in reducing the GHG emissions of vehicles has increased. A WTW analysis, which measures GHG emissions for all processes from feedstock recovery to vehicle operation, not just the GHGs emitted during vehicle operation, is being conducted for this purpose. Composed of a well-to-tank and a tank-to-wheel analysis, a WTW analysis calculates energy use and GHG emissions for each process (feedstock recovery, transport, fuel production, distribution, and vehicle operation) and finally presents a life cycle analysis of the GHG emissions of the vehicle. Because the situation of importing and producing fuel varies by country, it is important to establish a proper system boundary for each region. Furthermore, the process efficiency and fuel economy of vehicles may vary over time; therefore, calculating energy use and GHG emissions from the latest data is necessary.

Various WTW analyses were reported for internal combustion engines and electric vehicles in recent years. For instance, Woo reported the WTW analysis for electric vehicles based on electricity generation mix. As a result, some countries which produce electricity with high percentage of fossil fuels exhibited more GHG emissions of electric vehicles than internal combustion engine vehicles [5]. Bicer did a comparative WTW analysis of hydrogen, methanol and electric vehicles and found that hydrogen driven vehicles exhibited a more environmentally benign option compared with other vehicles [6].

The demand for green automobiles, including hydrogen, electric, natural gas, and LPG vehicles, has increased due to public interest in particulate matter issues in Korea. Among these vehicles, LPG vehicles have been used for taxis since 1982, but the purchase of these vehicles by the general public has been regulated in Korea. However, the LPG vehicle market is growing due to the implementation

†To whom correspondence should be addressed.
E-mail: kylee@korea.ac.kr
‡Min June Kim and Eun Jun Lee are co-first authors and have equally contributed to this work.

of the deregulation law allowing the general public to purchase these vehicles in 2019 [7]. LPG automobiles are recognized as eco-friendly because the nitrogen oxide and particulate emissions from these vehicles are significantly lower than those from diesel and gasoline vehicles. On the other hand, the lower fuel economy of LPG vehicles compared to that of gasoline and diesel vehicles has been considered to result in high emissions of greenhouse gas and low eco-friendliness. Thus, a comparative analysis of whether LPG vehicles are really eco-friendly in terms of life cycle is necessary.

There have been several studies conducted internationally on a WTW analysis of LPG fuel [8,9]. Unnasch studied the total GHG emissions of gasoline, diesel, and LPG vehicles in California based on greenhouse gases, Regulated Emissions, and Energy Use in Transportation Model (GREET) developed by Argonne National Laboratory (ANL). As a result, LPG from both crude oil and natural gas exhibited reduced WTW GHG emission compared with gasoline and diesel in California. However, the system boundary was aimed at California, which was different from that of Korea and the calculated WTW GHG emissions did not reflect the fuel economy of the vehicles being currently sold. Additionally, Boureima performed LCA analysis for electric hybrids, LPG and gasoline cars, including manufacturing and end of life vehicle. LPG vehicles showed reduced GHG emission compared to gasoline and comparable GHG emission with hybrid. But the GHG emissions in WTW phase were based on data from 20 years ago; therefore, it is difficult for the results to reflect the latest situation. Therefore, this study compared the GHG emissions of LPG and diesel vehicles in Korea by conducting a WTW analysis. Considering the life cycle of LPG and diesel fuels in Korea, a WTW analysis of LPG and diesel vehicles currently sold was conducted for each process, measuring and directly comparing energy consumption and GHG emissions based on the latest data.

## METHOD

### 1. LCA Model

The GREET model (GREET 2018) was used as the base model for LCA analysis [10]. The GREET model was developed by the Argonne National Laboratory (ANL). For various transportation equipment and fuels, the model enables a WTW analysis based on the actual situation in the United States. Many previous studies used the GREET model as the basic model for a WTW analysis [11-14]. This model can be used to calculate energy use and GHG emissions by setting variables, including process efficiency and process fuels, at each stage. In this study, GHG emissions were calculated based on $CO_2$ equivalent grams. The global warming potentials (GWPs) were also applied for $CO_2$, $CH_4$, and $N_2O$ as 1, 25, and 298, respectively. In the case of CO or VOC generated as a byproduct, the GHG emissions were calculated as the amount of $CO_2$ produced by complete oxidation.

For the feedstock recovery process, GREET data were modified by using the GHGenius model, because the energy use and GHG emissions vary from country to country [15]. The GHGenius is a WTT results program developed in Canada that includes data from several regional processes [11,14,16,17]. The GHGenius model is suitable for modifying existing data, as it considers recovery energy factors based on regional energy differences.

For the refinery, the GREET model cannot be applied separately to individual units (crude distillation unit, hydrocracker, etc.) used for each fuel product; thus, without proper allocation, only process efficiency can be adjusted to obtain the result. Therefore, we used the PRELIM model as a suitable model for the actual process [18,19]. The PRELIM model is a crude oil refining process LCA model developed by the National Energy Technology Laboratory (NETL) in the U.S. The PRELIM model can perform a proper calculation

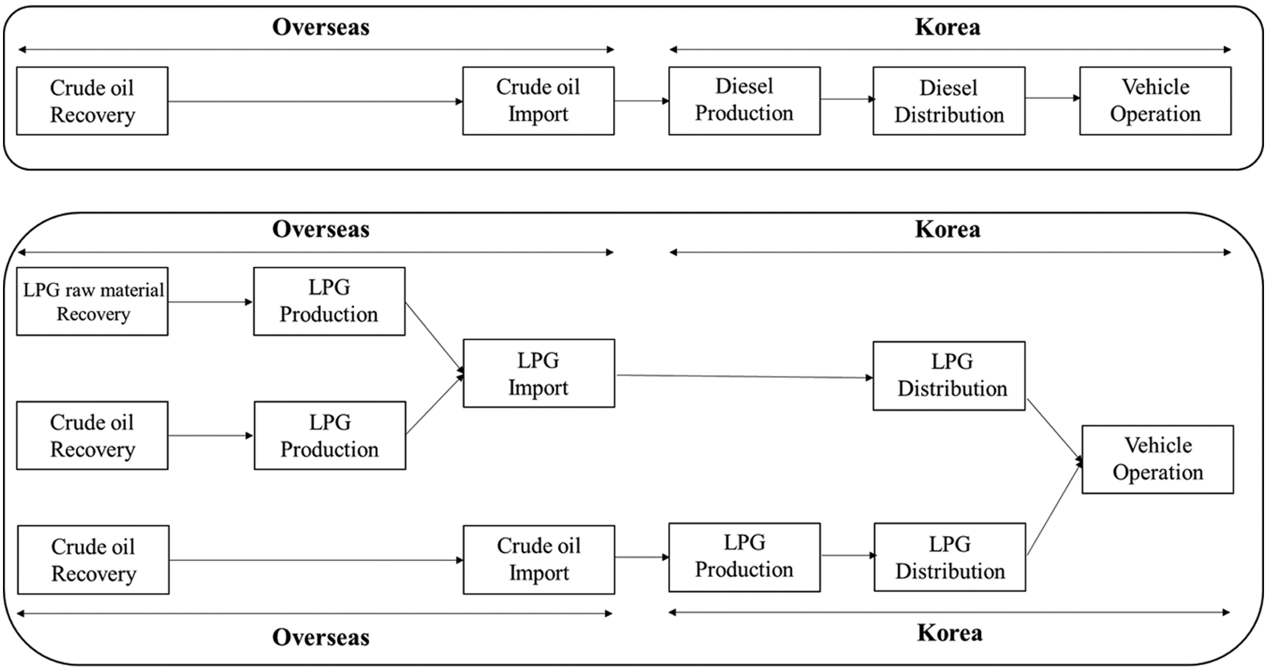


**Fig. 1. System boundary for diesel and LPG in Korea.**

for the situation according to the crude oil properties and process method [20]. In addition, enabling more realistic calculations, the energy use and GHG emissions can be calculated depending on the units used in the production process.

**2. System Boundary**

Fig. 1 shows the system boundary for LPG and diesel fuel use in Korea. In the case of diesel fuel, the life cycle is composed of a single set of processes: the crude oil recovery overseas, crude oil imported to Korea, diesel fuel production by refining in Korea, diesel distribution, and vehicle operation. In the case of LPG, the life cycle is composed of two sets of processes: (1) LPG fuel imported to Korea and (2) LPG production by refining crude oil in Korea. In this study, LPG production overseas was also divided into production from raw natural gas and production from crude oil. The ratio of each process was based on LPG production data in each country.

**3. Description of the Calculation Processes**

3-1. Feedstock Recovery

Feedstock recovery was calculated by using the GREET and GHGenius models. Because Korea imports crude oil and LPG from various overseas countries, we investigated Korea National Oil Corporation's 2018 import statistics, which showed the import volume from each country (Table S1, Table S2) [21]. Furthermore, scaling factors related to crude oil recovery energy in each country were applied by referring to the GHGenius model (Table S1, Table S2). In feedstock recovery, natural gas or waste gas was removed by combustion for safety in the oil production field or natural gas production field. Additionally, GHGs, including $CH_4$ and $CO_2$, can leak by venting. Therefore, GHG emissions from recovery energy (process fuels) for raw materials and GHG emission from flaring and venting were calculated. Recovery energy use and GHG emissions for the process fuels were calculated by considering the scaling factors for each country. GHG emissions from flaring and venting were calculated on the assumption that there was no regional difference.

According to the GREET model, which has information related to the recovery process in the United States (U.S.), the recovery energy for crude oil is 24.17 kJ/MJ, and GHG emissions, excluding flaring and venting, is 1.83 g $CO_2$ eq./MJ. The crude oil recovery energy factor, considering the scaling factors and the import ratio for each region, is 1.013 when the recovery energy factor of the U.S. is 1 (Table S1). Based on the recovery energy quantity (24.17 kJ/MJ in the U.S.) and the crude oil recovery energy factor (1.013), the crude oil recovery energy was finally determined to be 24.48 kJ/MJ of crude oil, and the GHG emissions, excluding venting and flaring, was 1.85 g $CO_2$ eq./MJ. According to the GREET model, the GHG emissions from flaring and venting was 3.30 g $CO_2$ eq./MJ (Table S3). Therefore, the GHG emission from crude oil recovery was 5.15 g $CO_2$ eq./MJ.

For natural gas raw material recovery, the U.S. and Middle East (Kuwait, Qatar, United Arab Emirates, and Saudi Arabia) factors should be considered. According to the GREET model, in the U. S. the recovery energy from natural gas raw materials is 32.99 kJ/MJ, and the GHG emission related to process fuels for recovery is 1.60 g $CO_2$ eq./MJ (Table S4). For the Middle East, 26.09 kJ/MJ of recovery energy is calculated by multiplying the non-U.S. extraction energy in the GREET model (Table S5) by a scaling factor (0.777). GHG emissions from recovery energy correspond to 1.23 g $CO_2$ eq./MJ. GHG emissions from flaring and venting also appear in natural gas recovery, corresponding to 4.03 g $CO_2$ eq./MJ, the amount of which is the same value for both the U.S. and the Middle East. Accordingly, recovery energy and GHG emission for natural gas raw material in U.S. are 26.09 kJ/MJ and 5.26 g/MJ. Those in non-U.S. are 32.99 kJ/MJ and 5.63 g/MJ.

3-2. Imports

Crude oil and LPG import calculations were performed by considering the distance from each country. The import distance was provided by the distance calculator in sea-distance.org, which provided the sailing distance from the overseas port to the port in Korea [22].

The crude oil import regions of Korea are Ulsan, Yeosu, and Daesan, which account for 50.1%, 27.0%, and 21.9% ratios, respectively, of the crude oil imports (Table S6). The LPG import regions of Korea are Ulsan and Pyeongtaek, which account for 71.2% and 28.8%, respectively, of the LPG imports (Table S8). Based on this data, the average transport distance of crude oil and LPG was 12,306 km and 16,853 km (Table S9, Table S10), respectively. In the case of LPG, bunker fuel consumption for the cooling of the LPG carrier and the loss of LPG by gasification should be considered. Based on a 47,000 ton capacity LPG carrier, the bunker fuel consumption for cooling and maintaining the temperature of the LPG carrier are 13 t/day and 2.5 t/day, respectively. Therefore, the additional bunker fuel amount was calculated by considering the transport time (21.7 days, average distance/LPG carrier speed) and the loading time, which was assumed to be two days, and this additional amount was included in the process fuel calculation. Furthermore, the loss of LPG by gasification should be considered for calculating energy use and GHG emissions. After LPG is imported, assuming that the boil-off rate of LPG is 0.086%/day, the residual LPG amount is 97.81% [23]. Finally, energy use and GHG emissions were calculated by multiplying the energy and emissions amounts by 100/97.81, including the amounts for all processes prior to import.

The results revealed that regarding imports produced overseas, 14.58 kJ/MJ of energy use and 1.39 g $CO_2$ eq./MJ of GHG emissions occur in crude oil imports and that 24.62 kJ/MJ of energy use and 2.02 g $CO_2$ eq./MJ of GHG emissions occur in LPG imports. Considering the ratio of fuel imports in Korea, diesel imports require 14.58 kJ/MJ of energy use and 1.39 g $CO_2$ eq./MJ of GHG emissions, and LPG imports require 22.00 kJ/MJ of energy use and 1.86 g $CO_2$ eq./MJ of GHG emission.

3-3. Fuel Production

The energy use and GHG emission for fuel production was calculated by the PRELIM model. In this study, crude oil composition was based on the most common "West Texas intermediate_Stratiev". In addition, we set up the deep conversion of Fluid Catalytic Cracking (FCC) and Gas oil-Hydrocracker (GO-HC) similar to that occurring in actual plants.

We set the refinery ratio according to the value of oil corporations in Korea. For a crude oil refinery, the diesel fuel produced only through boiler point refining in the crude distillation unit is equivalent to 38 wt% of the total output, while the remaining 62 wt% of diesel is produced through the hydrocracking process. The LPG produced through boiler point refining in the crude distillation unit is equivalent to 68 wt%, and the LPG produced through hydrocracking is 32 wt%.

According to the above mass fractions, diesel produced in the process of crude oil refining generates 136.00 kJ/MJ of energy use and 8.08 g $CO_2$ eq./MJ of GHG emissions. The energy use and GHG emissions of LPG produced by crude oil refining are 75.83 kJ/MJ and 4.95 g $CO_2$ eq./MJ, respectively. This difference is due to the high proportion of diesel produced by a hydrocracking process with high energy use and GHG emissions. In hydrocracking, LPG is considered as a byproduct so energy use and GHG emission from the hydrocracking process are excluded [8,24].

For LPG production from natural gas, the PRELIM model only considers that the LPG production stage produces LPG from fuel gas. The composition of fuel gas was calculated by setting the composition corresponding to natural gas (Table S11). The results of the calculation revealed that the energy use and GHG emissions are 10.09 kJ/MJ and 3.50 g $CO_2$ eq./MJ, respectively. The energy use and GHG emissions in the process of producing LPG from natural gas are lower than that in the previous process of producing diesel and LPG from crude oil because in the process of producing LPG from natural gas, there are no multistage processes, such as hydrocracking.

Finally, considering the ratio of the fuel production pathway, for diesel fuel the energy use and GHG emissions are 136.00 kJ/MJ and 8.08 g $CO_2$ eq./MJ, respectively. For LPG, import routes and production routes were considered; as a result the energy use and GHG emissions are 35.01 kJ/MJ and 4.10 g $CO_2$ eq./MJ, respectively (Table S7, Table S12) [25].

3-4. Distribution

The calculation of energy use and GHG emissions for distribution was performed by considering the consumption of diesel and LPG by each domestic region and the distance from the refinery and LPG import base to the region. The transport energy use and GHG emission values were utilized in the GREET model. In the case of diesel, we assumed that the fuel transportation share was 47% for pipelines, 32% for trucks, 20% for barges, and 1% for trains [26]. The LPG transportation calculation was performed with assumption that transportation was provided only by trucks, because it was known that LPG transportation depends entirely on truck in Korea.

The results revealed that considering the LPG distribution from the refinery and LPG imports, the energy use and GHG emission for diesel distribution are 1.68 kJ/MJ and 0.15 g $CO_2$ eq./MJ, respectively, and that the energy use and GHG emissions for LPG are 2.46 kJ/MJ and 0.23 g $CO_2$ eq./MJ, respectively. This difference between diesel and LPG resulted from the transportation share rather than the average distance.

3-5. Vehicle Operation

Energy use and GHG emissions in vehicle operation were calculated using the fuel economy and $CO_2$ emissions during the driving of diesel and LPG automobiles sold in Korea as of 2019. We compared four vehicles, which comprised both diesel and LPG models and had high sales volumes (two sedans, one sports utility vehicle (SUV), and a one-ton truck). Additionally, a relational expression was obtained by plotting the fuel economy and $CO_2$ emissions compared to the curb weight. We utilized this relational equation to calculate the fuel economy and $CO_2$ emissions of a 1,500 kg weight automobile, the weight of which corresponds to that of a midsize car (Fig. S1). The exhaust gases generated in vehicle operations contain GHG components other than $CO_2$, but under conditions that meet current exhaust regulations, the amount is extremely small compared to the amount of $CO_2$; therefore, the amount of exhaust gases was calculated by using only the $CO_2$ value. The fuel economy and $CO_2$ emissions during driving were based on the vehicle specifications provided by each vehicle manufacturer's official website (Table S16). As the values used in the WTT process are energy use and GHG emissions per unit of energy, a unit conversion was necessary to finally calculate the WTW result. Because the WTW result is based on per unit running distance (km), the conversion was performed by Eqs. (1) and (2), and the WTT value was added up with the vehicle operation value. Low heating values (LHV) were based on the GREET model (Diesel: 36.09 MJ/L, LPG: 23.67 MJ/L).

Fuel economy: x km/L; $CO_2$ emissions in vehicle operation: y g/km; LHV: z MJ/L

WTT result: Energy use: a kJ/MJ; GHG emission: b g $CO_2$ eq./MJ

$$\text{WTW GHG emission}=(y+(b\times z)/x)\ (\text{g } CO_2 \text{ eq./km}) \quad (1)$$

$$\text{WTW energy use}=(a\times z)/x+z/x\ (\text{kJ/km}) \quad (2)$$

## RESULTS AND DISCUSSION

### 1. Well-to-tank

Table 1 and Fig. 2 show the energy use and GHG emissions in the total WTT process, which is the sum of the feedstock recovery, import, fuel production, and distribution for diesel and LPG fuel in Korea. The value for LPG is a weighted-average value for energy use and GHG emissions for natural gas raw materials and crude oil. In terms of feedstock recovery and import per unit energy, the energy use and GHG emissions for LPG are larger than those

**Table 1. WTT energy use and GHG emissions of diesel and LPG**

| | Energy use (kJ/MJ) | | GHG emission (g $CO_2$ eq./MJ) | |
|---|---|---|---|---|
| | Diesel | LPG | Diesel | LPG |
| Recovery | 24.48 | 29.45 | 5.15 | 5.49 |
| Import | 14.58 | 22.00 | 1.39 | 1.86 |
| Production | 136.00 | 35.01 | 8.08 | 4.10 |
| Distribution | 1.68 | 2.46 | 0.15 | 0.23 |

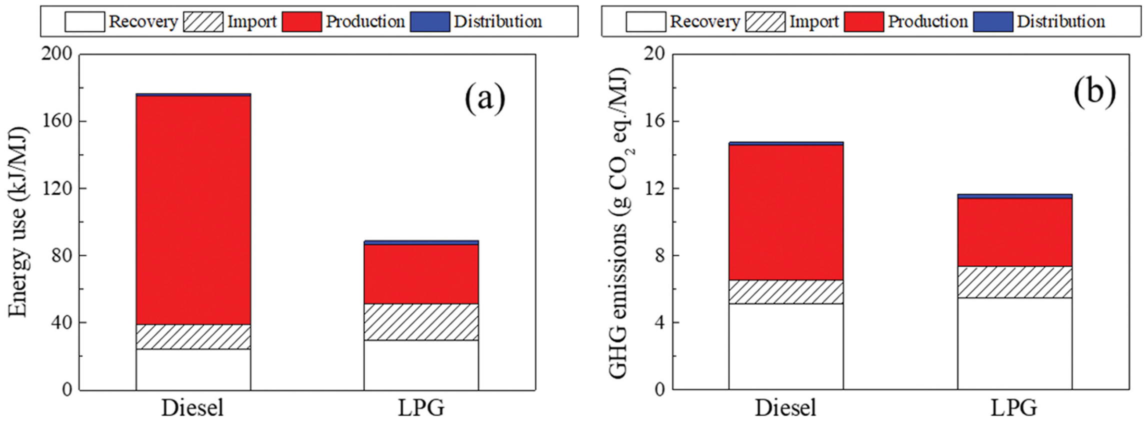


**Fig. 2. WTT (a) energy use and (b) GHG emissions of diesel and LPG.**

**Table 2. WTW energy use and GHG emissions of diesel and LPG**

| Fuel | Diesel | | LPG | |
|---|---|---|---|---|
| | Energy use | GHG emission | Energy use | GHG emission |
| 1,500 kg | 2,839 kJ/km | 164.07 g $CO_2$ eq./km | 2,940 kJ/km | 185.84 g $CO_2$ eq./km |
| Sedan A | 2,383 kJ/km | 133.95 g $CO_2$ eq./km | 2,432 kJ/km | 148.08 g $CO_2$ eq./km |
| Sedan B | 2,719 kJ/km | 154.18 g $CO_2$ eq./km | 2,631 kJ/km | 161.21 g $CO_2$ eq./km |
| SUV | 2,887 kJ/km | 195.65 g $CO_2$ eq./km | 2,967 kJ/km | 183.20 g $CO_2$ eq./km |
| 1 ton truck | 4,284 kJ/km | 248.85 g $CO_2$ eq./km | 3,967 kJ/km | 244.53 g $CO_2$ eq./km |

of diesel fuel. However, the values for LPG production are significantly lower than those of diesel production, because unlike diesel production, which requires a high ratio of hydrogenation from crude oil, LPG production requires a small ratio of hydrogenation; therefore, there are differences in energy use and GHG emissions resulting from the production process. It can be verified that in Korea, the proportion of distribution in the WTT process is very small. Finally, LPG was confirmed to be more advantageous than diesel in terms of energy use and GHG emission per unit energy in the WTT.

**2. Well-to-wheel**

Table 2 and Fig. 3 show the WTW values of four vehicles sold in Korea and the 1,500 kg weight model. The WTW results of each automobile were calculated by summing the WTT results through conversion into a value per unit mileage, as described for the TTW value in section 2.3.5. The TTW GHG emissions comprise a large proportion (approximately 80%) of the total WTW GHG emissions in both diesel and LPG vehicles, as shown in Fig. 3. This means that the $CO_2$ emissions in vehicle operation correspond to the main factor in the life cycle of most internal combustion engine vehicles. In the case of the two sedans and the 1,500 kg model, the WTW GHG emissions are lower in diesel automobiles than in the LPG automobile. On the other hand, WTW GHG emissions show the opposite tendency in the SUV and the one-ton truck. This tendency resulted from the fuel economy ($CO_2$ emissions in vehicle operation) difference between the diesel and LPG model of the same vehicle. The model's fuel economy was the main factor affecting the amount of total WTW GHG emissions, as shown in Table 2. LPG showed a lower generation of GHG emissions per unit energy in WTT processes, but in measuring WTW GHG emissions, it can be seen that WTT GHG emissions have a relatively insignificant effect compared to that of TTW GHG emissions. However, the fuel economy of vehicles may be improved in the future, the proportion of WTT GHG emission in WTW GHG emissions is expected to increase and the trend may change. Finally, the WTW results in Korea reveal that the GHG emissions from diesel fuel are lower in small weight vehicles (two sedans and the 1,500 kg weight model), and the GHG emissions from LPG are lower in relatively larger weight vehicles (SUV, one-ton truck).

## CONCLUSION

In this study, based on the GREET model and the PRELIM model, we calculated GHG emissions and the energy use of diesel and LPG vehicles in Korea.

For WTT, LPG's energy use and GHG emissions were calculated to be significantly lower than that of diesel. Because diesel includes a hydrocracking process in the fuel production process, in WTT processes, diesel fuel requires more energy use and creates more GHG emissions than does LPG fuel.

In the WTW processes, the resulting energy and emissions values depend on the fuel economy; therefore, these values vary depending on the vehicle. For an SUV and a one ton truck, LPG's GHG emission per mileage was lower than that of diesel fuel. For the two sedans and the 1,500 kg model, LPG's GHG emission per mileage was higher than that of diesel. It is expected that the GHG emissions of LPG vehicles will be improved through improved fuel efficiency resulting from the development of next generation

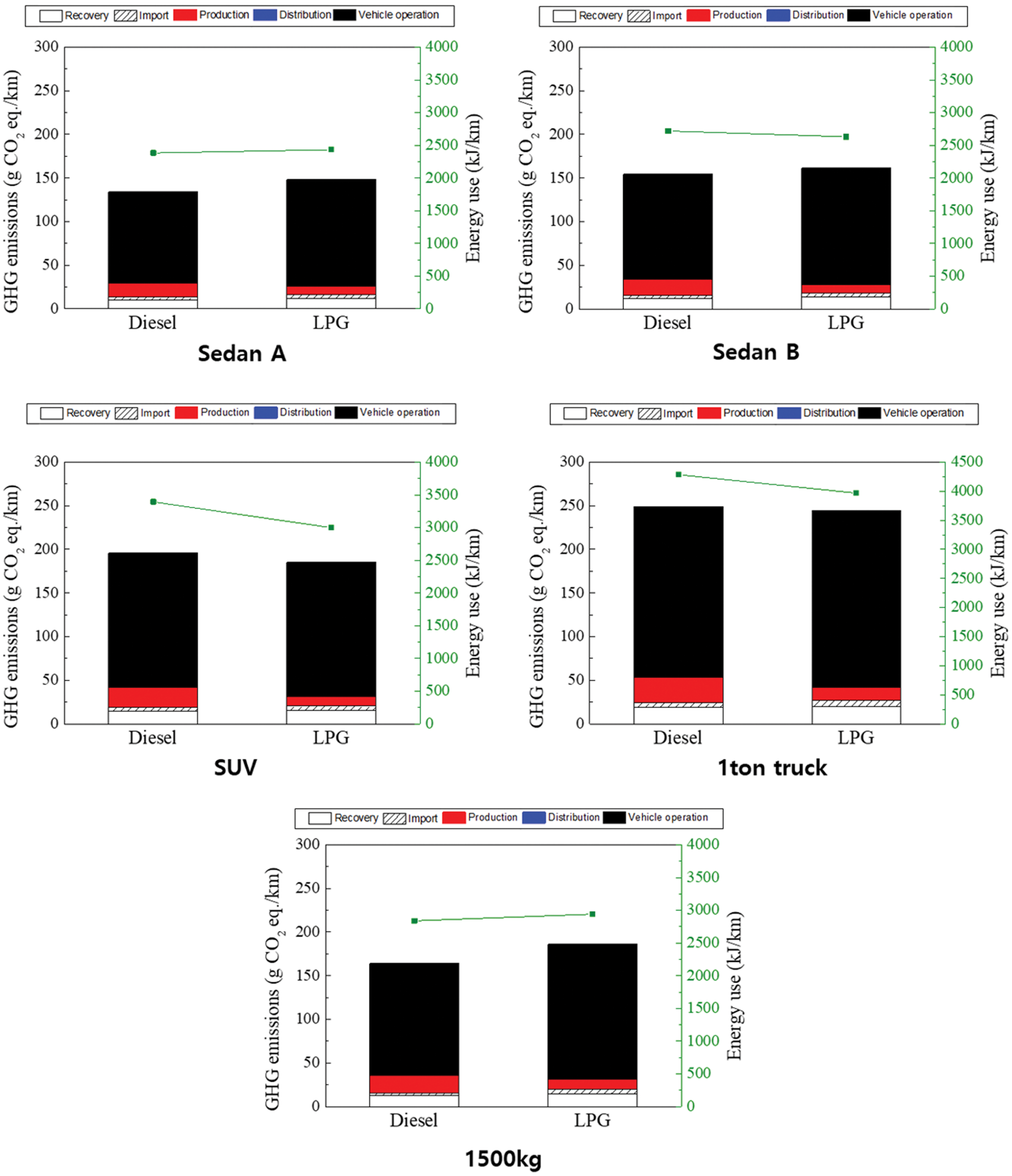


**Fig. 3. WTW energy use and GHG emissions of diesel and LPG.**

LPG engines, such as T-LPDi. In later research, a study comparing vehicles using the next generation engine with hydrogen or electric powered vehicles is suggested.

## ACKNOWLEDGEMENT

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## SUPPORTING INFORMATION

Additional information as noted in the text. This information is available via the Internet at http://www.springer.com/chemistry/journal/11814.

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# Supporting Information

# Life cycle assessment of LPG and diesel vehicles in Korea

**Min June Kim[*,‡], Eun Jun Lee[*,‡], Chul-Jin Kim[**], Ung Gi Hong[**], Deuk Soo Park[**], Haebin Shin[**], and Kwan-Young Lee[*,***,****,†]**

*Department of Chemical and Biological Engineering, Korea University, 145 Anam-ro, Seongbuk-gu, Seoul 02841, Korea
**SK Gas, ECO Hub, 332 Pangyo-ro, Bundang-gu, Seongnam-si, Gyeonggi-do 13493, Korea
***Super Ultra Low Energy and Emission Vehicle (SULEEV) Center, Korea University,
145 Anam-ro, Seongbuk-gu, Seoul 02841, Korea
****Graduate School of Energy and Environment (KU-KIST Green School), Korea University, Seoul 02841, Korea
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**Table S1. The import volume of crude oil in Korea by country in 2018 and recovery energy factor**

| | Crude oil import volume (1,000 Bbl)* | Ratio (%) | Recovery energy factor** |
|---|---|---|---|
| Australia | 11,092 | 1.04% | 0.92 |
| Russia | 39,323 | 3.69% | 1.05 |
| Kazakhstan | 55,434 | 5.20% | 1.06 |
| Algeria | 15,738 | 1.48% | 0.68 |
| United states | 60,942 | 5.72% | 1 |
| Mexico | 31,966 | 3.00% | 1.39 |
| Iran | 58,202 | 5.46% | 1.05 |
| Iraq | 138,131 | 13.0% | 1.1 |
| Kuwait | 162,005 | 15.20% | 1.05 |
| Qatar | 65,980 | 6.19% | 1.05 |
| United arab emirates | 72,030 | 6.76% | 1.06 |
| Saudi arabia | 323,174 | 30.33% | 0.91 |
| United kingdom | 31,360 | 2.94% | 0.95 |

*Korea National Oil Corporation's 2018 crude oil import statistics (except for country accounted for less 1% of total import).
**Recovery energy factor by country when recovery energy of U.S. is 1 in GHGenius 5.0 model.

**Table S2. The import volume of LPG in Korea by country in 2018 and extraction energy factor**

| | LPG import volume (1,000 Bbl)* | Ratio (%) | Extraction energy factor** |
|---|---|---|---|
| United states | 61,966 | 81.89 | 1 |
| Kuwait | 3,791 | 5.01 | 0.7770 |
| Qatar | 3,819 | 5.05 | 0.7770 |
| United arab emirates | 4,771 | 6.30 | 0.7770 |
| Saudi arabia | 1,322 | 1.75 | 0.7770 |

*Korea National Oil Corporation's 2018 LPG import statistics (except for country accounted for less 1% of total import).
**Extraction energy factor by country when recovery energy of U.S. is 1 in GHGenius 5.0 model.

**Table S3. Crude oil recovery energy and venting, flaring, and fugitive (VFF) in U.S.**

| U.S. | GREET 2018 |
|---|---|
| Recovery efficiency | 98% |
| Energy use (per 1 MJ of crude oil) | |
| Natural gas | 16.43 kJ |
| Electricity | 3,872.15 J |
| Diesel for non road applications | 3,056.96 J |
| Gasoline Blendstock | 407.6 J |
| Crude oil | 203.80 J |
| Residual oil | 203.80 J |
| **Total energy use** | 24.17 kJ |
| Crude production fugitive emissions (per 1 MJ of crude oil) | |
| Flared natural gas | 0 |
| Venting flaring fugitive $CH_4$ | 75.8 mg |
| Venting flaring fugitive $CO_2$ | 1.026 g |

**Table S4. Raw natural gas recovery energy and VFF in U.S.**

| U.S. | Extraction |
|---|---|
| Recovery efficiency | 96.9% |
| Energy use (per 1 MJ of natural gas) | |
| Natural gas | 29.5 kJ |
| Electricity | 249.65 J |
| Diesel for non road applications | 2,746.11 J |
| Gasoline blendstock | 249.64 J |
| Crude oil | 0 J |
| Residual oil | 249.64 J |
| **Total energy use** | 32.99 kJ |
| Natural gas production fugitive emissions (per 1 MJ of natural gas) | |
| Flared natural gas | 1.613 Btu |
| Venting flaring fugitive $CH_4$ | 139.2 mg |
| Venting flaring fugitive $CO_2$ | 18.9 mg |

**Table S5. Raw natural gas recovery energy and VFF in Non-U.S.**

| Non-U.S. | Extraction |
|---|---|
| Recovery efficiency | 96.7% |
| Energy use (per 1 MJ of natural gas) | |
| Natural gas | 30 kJ |
| Electricity | 256.00 J |
| Diesel for non road applications | 2,816.04 J |
| Gasoline blendstock | 256 J |
| Crude oil | 0 J |
| Residual oil | 256 J |
| Total energy use | 33.58 kJ |
| Natural gas production fugitive emissions (per 1 MJ of natural gas) | |
| Flared natural gas | 1.658 Btu |
| Venting flaring fugitive $CH_4$ | 129.95 mg |
| Venting flaring fugitive $CO_2$ | 18.04 mg |

**Table S6. Crude oil import volume in Korea**

| | Crude oil (Bbl/day) | Ratio (%) |
|---|---|---|
| Ulsan | 1,509,000 | 50.1 |
| Yeosu | 800,000 | 27.0 |
| Daesan | 650,000 | 21.9 |

**Table S7. LPG import and production volume in Korea**

| | LPG (1,000 Bbl)* | Ratio (%) |
|---|---|---|
| LPG import volume | 79,325 | 70.06 |
| LPG production volume in Korea | 33,900 | 29.94 |

*Korea National Oil Corporation's 2018 LPG import and production statistics.

**Table S8. LPG import volume in Korea by import terminal**

| | LPG (ton) | Ratio (%) |
|---|---|---|
| Ulsan | 2,708,705 | 71.20 |
| Pyeongtaek | 1,095,745 | 28.80 |

*Based on SK Gas corporation's import statics. It was assumed that the import tendency of Korea was same as SK Gas corporation's import.

**Table S9. Crude oil import distance**

| | Import volume (1,000 Bbl) | Ratio (%) | Distance (km) (Ulsan) | Distance (km) (Yeosu) | Distance (km) (Daesan) |
|---|---|---|---|---|---|
| Australia | 11,092 | 1.04% | 6,584 | 6,486 | 6,776 |
| Russia | 39,323 | 3.69% | 16,273 | 16,136 | 16,354 |
| Kazakhstan | 55,434 | 5.20% | 16,273 | 16,136 | 16,354 |
| Algeria | 15,738 | 1.48% | 17,083 | 16,946 | 17,163 |
| United states | 60,942 | 5.72% | 9,738 | 9,825 | 10,468 |
| Mexico | 31,966 | 3.00% | 17,592 | 17,711 | 18,349 |
| Iran | 58,202 | 5.46% | 10,949 | 10,812 | 11,030 |
| Iraq | 138,131 | 13.0% | 11,900 | 11,764 | 11,981 |
| Kuwait | 162,005 | 15.20% | 11,808 | 11,671 | 11,889 |
| Qatar | 65,980 | 6.19% | 11,275 | 11,138 | 11,355 |
| United arab emirates | 72,030 | 6.76% | 11,040 | 10,903 | 11,120 |
| Saudi arabia | 323,174 | 30.33% | 11,541 | 11,405 | 11,622 |
| United kingdom | 31,360 | 2.94% | 19,407 | 19,270 | 19,488 |
| Total | 1,065,377 | 100% | 12,446 | 12,191 | 12,307 |
| Average import distance | | | | 12,306 | |

**Table S10. LPG import distance**

| | Import volume (1,000 Bbl) | Ratio (%) | Distance (km) (Ulsan) | Distance (km) (Pyeongtaek) |
|---|---|---|---|---|
| United states | 61,966 | 81.89 | 17,829 | 18,553 |
| Kuwait | 3,791 | 5.01 | 11,765 | 11,813 |
| Qatar | 3,819 | 5.05 | 11,359 | 11,420 |
| United arab emirates | 4,771 | 6.30 | 11,343 | 11,391 |
| Saudi arabia | 1,322 | 1.75 | 11,539 | 11,587 |
| Total | 75,669 | 100 | 16,680 | 17,282 |
| Average import distance | | | 16,853 | |

**Table S11. Natural gas composition**

| Component | Composition ratio (mole %) |
|---|---|
| C1 | 90.63 |
| C2 | 5.24 |
| C3 | 2.34 |
| C4 | 1.11 |
| C5+ | 0.69 |

**Table S12. LPG production ratio based on resource**

| LPG production ratio | From natural gas (%)* | From crude oil (%)* |
|---|---|---|
| Korea | 0 | 100 |
| United states | 88.27 | 11.73 |
| Kuwait | 96.88 | 3.12 |
| Qatar | 96.71 | 3.29 |
| United arab emirates | 88.61 | 11.39 |
| Saudi arabia | 91.89 | 8.11 |

*Based on Knoema.com data.

**Table S13. Diesel consumption of each region and distance from refinery**

| | Consumption [1,000 Bbl] | Ratio (%) | Refinery | Distance (km) |
|---|---|---|---|---|
| Seoul | 11,883 | 7.11% | Daesan | 125 |
| Busan | 8,535 | 5.11% | Ulsan | 58 |
| Daegu | 4,982 | 2.98% | Ulsan | 112 |
| Incheon | 8,173 | 4.89% | Daesan | 117 |
| Gwangju | 3,857 | 2.31% | Yeosu | 121 |
| Daejeon | 3,901 | 2.34% | Daesan | 134 |
| Ulsan | 5,353 | 3.21% | Ulsan | 16 |
| Sejong | 676 | 0.41% | Daesan | 123 |
| Gyeonggi province | 41,363 | 24.8% | Daesan | 175 |
| Gangwon province | 7,731 | 4.63% | Daesan | 272 |
| North Chungcheong province | 8,542 | 5.11% | Daesan | 146 |
| South Chungcheong province | 11,388 | 6.82% | Daesan | 76 |
| North Jeolla province | 9,013 | 5.40% | Yeosu | 134 |
| South Jeolla province | 11,283 | 6.76% | Yeosu | 88 |
| North Gyeongsang province | 13,598 | 8.14% | Ulsan | 213 |
| South Gyeongsang province | 13,990 | 8.38% | Ulsan | 127 |
| Jeju province | 2,772 | 1.66% | Yeosu | 234 |

**Table S14. LPG consumption of each region and distance from LPG import terminal (70% of total LPG consumption in Korea)**

| | Consumption [1,000 Bbl] | Ratio (%) | Terminal | Distance (km) |
|---|---|---|---|---|
| Seoul | 7,760 | 7.07% | Pyeongtaek | 74 |
| Busan | 3,411 | 3.11% | Ulsan | 58 |
| Daegu | 2,414 | 2.20% | Ulsan | 112 |
| Incheon | 3,080 | 2.81% | Pyeongtaek | 62 |
| Gwangju | 1,883 | 1.71% | Ulsan | 281 |
| Daejeon | 1,499 | 1.3% | Pyeongtaek | 100 |
| Ulsan | 29,976 | 27.3% | Ulsan | 16 |
| Sejong | 255 | 0.23% | Pyeongtaek | 76 |
| Gyeonggi province | 17,736 | 16.15% | Pyeongtaek | 131 |
| Gangwon province | 2,364 | 2.15% | Pyeongtaek | 218 |
| North Chungcheong province | 3,008 | 2.74% | Pyeongtaek | 77 |
| South Chungcheong province | 12,100 | 11.02% | Pyeongtaek | 55 |
| North Jeolla province | 2,616 | 2.38% | Ulsan | 256 |
| South Jeolla province | 10,233 | 9.32% | Ulsan | 263 |
| North Gyeongsang province | 4,659 | 4.24% | Ulsan | 213 |
| South Gyeongsang province | 5,227 | 4.76% | Ulsan | 127 |
| Jeju province | 1,557 | 1.42% | Ulsan | 361 |

**Table S15. LPG consumption of each region and distance from refinery (30% of total LPG consumption in Korea)**

| | Consumption [1,000 Bbl] | Ratio (%) | Refinery | Distance (km) |
|---|---|---|---|---|
| Seoul | 7,760 | 7.07% | Daesan | 125 |
| Busan | 3,411 | 3.11% | Ulsan | 58 |
| Daegu | 2,414 | 2.20% | Ulsan | 112 |
| Incheon | 3,080 | 2.81% | Daesan | 117 |
| Gwangju | 1,883 | 1.71% | Yeosu | 121 |
| Daejeon | 1,499 | 1.3% | Daesan | 134 |
| Ulsan | 29,976 | 27.3% | Ulsan | 16 |
| Sejong | 255 | 0.23% | Daesan | 123 |
| Gyeonggi province | 17,736 | 16.15% | Daesan | 175 |
| Gangwon province | 2,364 | 2.15% | Daesan | 272 |
| North Chungcheong province | 3,008 | 2.74% | Daesan | 146 |
| South Chungcheong province | 12,100 | 11.02% | Daesan | 76 |
| North Jeolla province | 2,616 | 2.38% | Yeosu | 134 |
| South Jeolla province | 10,233 | 9.32% | Yeosu | 88 |
| North Gyeongsang province | 4,659 | 4.24% | Ulsan | 213 |
| South Gyeongsang province | 5,227 | 4.76% | Ulsan | 127 |
| Jeju province | 1,557 | 1.42% | Yeosu | 234 |

**Table S16. Fuel economy and $CO_2$ emission in vehicle operation of automobiles**

| | Fuel economy (km/L) | | $CO_2$ emission in vehicle operation (g/km) | |
|---|---|---|---|---|
| | Diesel | LPG | Diesel | LPG |
| Sedan A | 17.8 | 10.6 | 104 | 122 |
| Sedan B | 15.6 | 9.8 | 120 | 133 |
| SUV | 12.5 | 8.6 | 153 | 153 |
| 1 ton truck | 9.9 | 6.5 | 195 | 202 |
| 1,500 kg | 14.94 | 8.77 | 128.4 | 154.3 |

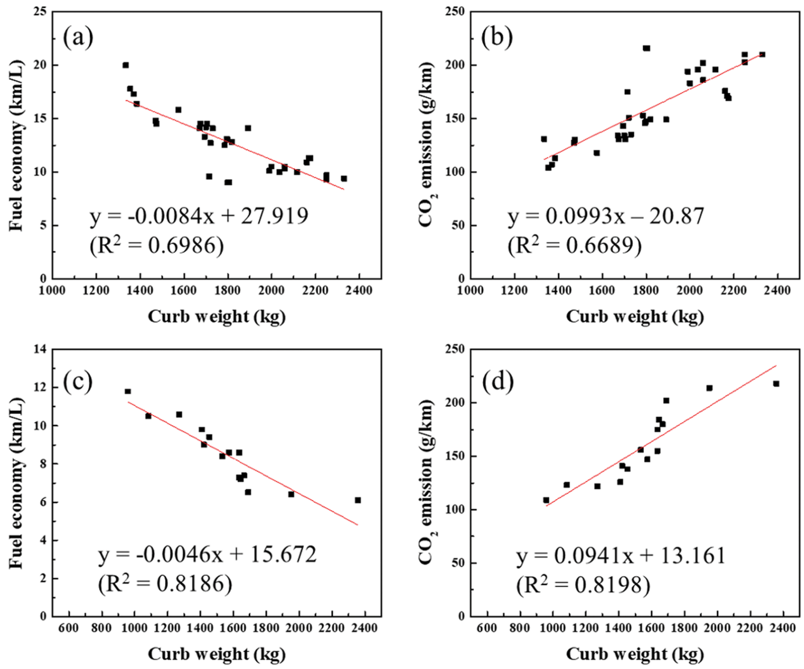


**Fig. S1. Plots of (a) fuel economy of diesel, (b) $CO_2$ emissions of diesel, (c) fuel economy of LPG, and (d) $CO_2$ emissions of LPG vs. curb weight of vehicles.**