REVIEW OF LIFE CYCLE GHG EMISSIONS FROM LPG RIDING MOWERS

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1. Summary

This paper examines the greenhouse gas (GHG) emissions from liquefied petroleum gas (LPG) and conventional fueled riding mowers. Emissions are calculated on a well-to-wheel (WTW) basis which includes the production of feedstock, transport to refining, refining, distribution, and end use in the mower.

The full fuel cycle emissions from LPG and other transportation fuels are examined in well to wheel (WTW) models such as GREET[1], which is primarily for on-road transportation applications, but has been adapted to off-road applications as well. This paper uses the CA-GREET model that is used for the California Low Carbon Fuel Standard (LCFS)[2].
Several pathways for LPG are examined in CA-GREET. These include production of LPG from natural gas liquids and from crude oil refining. The use of LPG is specifically examined in CA-GREET for passenger car and heavy duty vehicle operation.

The sources of emissions for each step in the fuel cycle are given in Table 1 for natural gas and petroleum derived LPG. The steps in the fuel pathway are consistent with conventional oil and gas pathways, with different assumptions on processing efficiency and transportation mode.

The WTW results for LPG from the CA-GREET model are shown in Figure 1. The upstream fuel cycle results and engine emissions are adjusted for the engine efficiency based on EPA emission factors for mowers.

[1] ANL (2010) The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model, Version 1.8d.0, Argonne National Laboratory. http://www.transportation.anl.gov/modeling_simulation/GREET/index.html.
[2] ARB (2009) California-GREET Model, Version 1.8b, Life Cycle Associates, based on GREET 1.8b by ANL. http://www.arb.ca.gov/fuels/lcfs/lcfs.htm.

Table 1. Pathway Steps for LPG Fuels in GREET Analysis

Step	Petroleum LPG	Natural Gas LPG
Feedstock Production	Crude Oil Extraction, Associated gas venting and flaring. Same emissions applied to gasoline	Natural gas extraction, fugitive losses. Natural gas recovery. Same emissions applied to natural gas pathways
Feedstock Transport	Transport of crude oil to oil refinery. Same emission applied to gasoline. Transport of LPG to distribution centers	Transport of LPG to distribution centers
Refining	Oil refinery emissions with efficiency input for LPG	LPG refining
Product Transport	Transport to local fuel station	Transport to local fuel station
Fuel Combustion	Carbon in fuel converted to CO_2 plus Vehicle CH_4 and N_2O emissions	

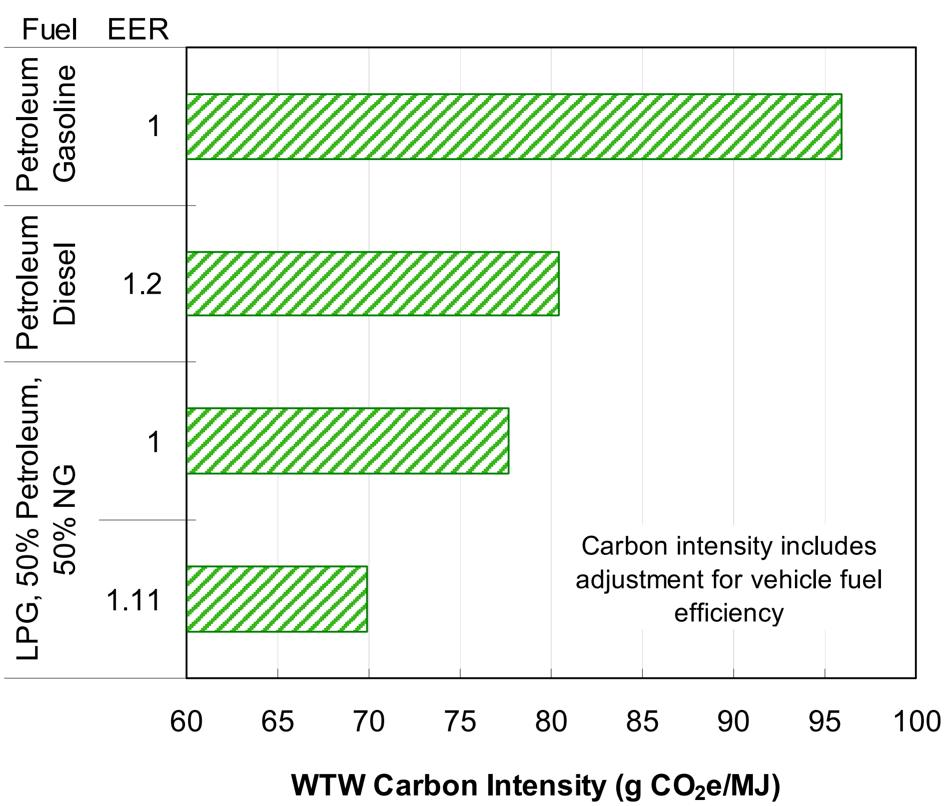

Figure 1. Comparison of WTW Emissions from LPG, Gasoline, and Diesel Mowers (adjusted for engine efficiency, EER from EPA data[3],[4])

[3] Exhaust Emission Factors for Nonroad Engine Modeling - Spark-Ignition, EPA-420-P-10-019, July 2010. Phase 2 (post 2007)

The results presented in Figure 1 show that LPG-fueled (on a mix of 50% petroleum-derived LPG and 50% natural gas-derived LPG) mowers have 27% lower GHG emissions (g CO_2e/MJ fuel) than comparable gasoline-fueled mowers as calculated in this study. This result depends on three factors:

- The reduced carbon content (gC/MJ fuel) of LPG compared to gasoline and diesel fuel
- Reduced upstream refining energy for LPG compared to gasoline and diesel
- Increased engine efficiency for LPG-fueled mowers compared to gasoline and diesel mowers in the EPA data

The lower carbon content of LPG compared to gasoline or diesel is well known. The combination of carbon content and fuel upstream energy results in a reduction of 20g of carbon dioxide equivalent emissions (g CO_2e) per megajoule (MJ) fuel compared to gasoline or diesel, or about a 20% reduction in GHG emissions. CA-GREET model inputs for refining energy assume that LPG production is a co-product of crude oil refining and the refining efficiency is better for LPG than that of gasoline[5].

Engine efficiency directly affects GHG emissions because CO_2 from fuel combustion and upstream fuel cycle emissions are proportional to relative fuel consumption. EPA emission factors for mowers were used to calculate an energy economy ratio (EER) to adjust the GHG emissions for efficiency. EER is defined to be ratio of the energy consumption (e.g., the break-specific fuel consumption – BSFC) of an equivalent baseline standard vehicle to that of the alternative fueled vehicle. In the case of light-duty vehicles such as LPG riding mowers, the baseline standard is an equivalent gasoline-fueled vehicle, Thus, alternative fueled vehicles with EER greater than 1.0 are more energy efficient (i.e. have better fuel economy on a MJ/mi basis) than the equivalent gasoline fueled vehicle. Interestingly, in the EPA data the EER for LPG mowers shows an 11% improvement over gasoline mower engines. Since these differences may be due to engine size and model disparities, and perhaps due to a limited data set for the EPA data, this efficiency improvement may not be realized in a more representative engine population. Thus, the GHG emissions were also examined for LPG engines with the same assumed efficiency as gasoline engines. With the EER of 1.0 (no engine efficiency improvement for an LPG engine on a BSFC basis), the decreased fuel carbon content and decreased upstream refining energy of LPG result in GHG emissions from LPG mowers that are still 20% below those from gasoline mowers.

2. LCA Methods and Approach

The life cycle GHG emissions from LPG-fueled engine are calculated in various fuel LCA models including GREET, GHGenius, Jacobs refining LCA model, and the JRC WTW study[6].

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[4] "Exhaust Emission Factors for Nonroad Engine Modeling - Compression-Ignition, EPA Report No. NR-009A, June 1998. Tier 2 (post 2004)"

[5] Note that the latest ANL GREET_1.8d.1 uses the same efficiency assumption for gasoline and LPG thereby eliminating any difference from the oil refinery.

[6] ARB (20091) California-GREET Model, Version 1.8b, Life Cycle Associates, based on GREET 1.8b by ANL. http://www.arb.ca.gov/fuels/lcfs/lcfs.htm.

This study uses the CA-GREET model. The CA-GREET model was chosen because it has become the model of choice for use in California, and is the model the California Air Resources Board (ARB) uses to do LCAs for transportation fuels. It is the LCA model ARB has used, and continues to use to quantify the GHG emissions of fuel pathways to comply with the LCFS. The CA-GREET values are used for calculations of the LPG components in other fuel pathways in the LCFS. The CA-GREET model also calculates the baseline gasoline and diesel results.

2.1 WTW Steps

The steps in the fuel cycle on petroleum fuels are shown in Figure 2. The primary pathways for LPG in the GREET model are as a co-product of petroleum derived or natural gas derived fuels. LPG is assigned a share of the emissions from oil production and transport to oil refineries. The pathways for crude oil and natural gas production are parallel.

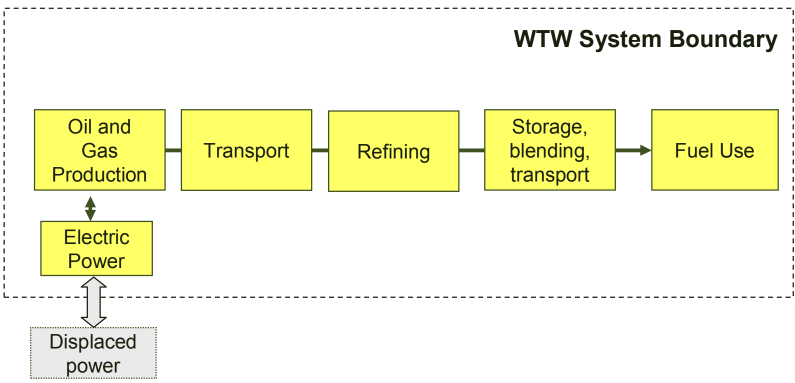

Figure 2. Steps in fossil fuel life cycle

2.2 Life Cycle Criteria

2.2.1 GHG Emissions

GHG impacts are compared through the global warming potential (GWP) weighted emissions for the primary GHG emissions associated with fuel combustion – CO2, CH4, and N2O. GHG emissions are weighted according to the IPCC 2007 assessment. Emissions of these gases are weighted by factors of 1, 25, and 298 respectively. These values are used in the CA-GREET model used for the LCFS.

ANL (2010) The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model, Version 1.8d.0, Argonne National Laboratory. http://www.transportation.anl.gov/modeling_simulation/GREET/index.html

$(S\&T)^2$ Consultants. (2010) GHGenius 3.17, February 2010. http://www.ghgenius.ca/

Keesom, W., Unnasch S., and Moretta J. (2009) Life Cycle Assessment Comparison of North American and Imported Crudes, Jacobs, AERI.

JEC (2008) Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context. Well to Tank Report, Version 3, October 2008.

2.2.2 Functional Unit

CA-GREET calculates emissions in well to tank and tank to wheel steps. Well to tank emissions include those associated with producing feedstock through its distribution. These emissions are presented per million Btu (mmBtu) of fuel in the model. The vehicle emissions are represented per mile traveled and are calculated based on the carbon in fuel per mmBtu and fuel use per mile. CA-GREET outputs are all presented in g/mi. These outputs are highly aggregated and difficult to compare to other model results because the baseline petroleum vehicle is usually different in each model.

The WTW comparisons presented here show the emissions per MJ of fuel. Any effect of vehicle efficiency is adjusted with an energy economy ratio (EER) adjustment. This approach is used with the California LCFS regulations. GHG emissions presented in this manner are referred to as the carbon intensity (CI).

3. LCA Inputs

3.1 Riding Mower Emissions

The operation of riding mowers requires power from an engine to drive the cutter blades and provide motive power to the mower. Comparing LPG to gasoline or diesel powered mowers requires a comparable unit of power to compare the energy inputs and emissions. Engines are typically rated in terms of their brake specific fuel consumption (bsfc) in g fuel per horsepower hour of work (g/hp-hr). Assuming that the work in hp-hr required to mow the same landscape surface is the same for LPG and gasoline or diesel mowers, then the emissions per hp-hr of work provides a meaningful comparison of the mower emissions.

The emissions can also be compared on a per-MJ of fuel burned basis, which compares LPG and gasoline fuels assuming that the mower engines have the same efficiency. The carbon intensity is adjusted for the mower efficiency as described in Section 4. The MJ metric of comparison is referred to as the functional unit as discussed in Section 2. This metric of comparison is consistent with other fuel LCA studies and policies.

The primary inputs to the CA-GREET model reflect energy inputs and fugitive emissions. Energy inputs are converted to combustion emissions and fugitive emissions are assumed to decompose to CO_2 in the atmosphere.

The inputs to the CA-GREET model are shown in Table 2. The key parameters are the efficiency for crude oil extraction and refining efficiency. Differences in refining efficiency are translated into differences in the upstream fuel cycle emissions.

Table 2. CA-GREET Model Inputs for Petroleum LPG

Crude Oil Refining

Refining Efficiency	**Efficiency**	**J/MJ Produt**
RBOB	84.5%	183,432
ULSD	86.8%	152,074
Diesel	87.0%	149,425
LPG	92.0%	86,957
Active Case	LPG	86,957
Crude refining fuel shares		
Crude Oil	0.0%	0
Residual Oil	3.0%	2,609
Diesel	0.0%	0
Gasoline	0.0%	0
Natural Gas	30.0%	26,087
Coal (Pet Coke)	13.0%	11,304
Electricity	4.0%	3,478
Refinery Still Gas	50.0%	43,478
Feed loss	0.0%	
Electricity Generation Mix for Crude Refining		
Electricity mix	CA_Average	

Transport & Distribution

Fuel Transport and Distribution	Product Transport					Distribution	
Transport of Finished Product	**Ocean Tanker**	**Barge**	**Pipeline**	**Rail**	**Truck**	**Pipeline**	**Truck**
Distance (mi)	8,800	200	50	50	50	50	50
RBOB	0.0%	0.0%	100.0%	0.0%	0.0%	0.6%	99.4%
Diesel	0.0%	0.0%	100.0%	0.0%	0.0%	0.6%	99.4%
LPG	0.0%	0.0%	0.0%	50.0%	50.0%		100.0%
Residual Oil	50.0%			50.0%			
Petroleum Coke	50.0%	0.0%	0.0%	50.0%	0.0%		

Table 2. CA-GREET Model Inputs for Petroleum LPG (Concluded)

Crude Oil Refining

Refining Efficiency	Efficiency	J/MJ Produt
RBOB	84.5%	183,432
ULSD	86.8%	152,074
Diesel	87.0%	149,425
LPG	92.0%	86,957
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Transport & Distribution

Fuel Transport and Distribution	Product Transport					Distribution	
Transport of Finished Product	**Ocean Tanker**	**Barge**	**Pipeline**	**Rail**	**Truck**	**Pipeline**	**Truck**
Distance (mi)	8,800	200	50	50	50	50	50
RBOB	0.0%	0.0%	100.0%	0.0%	0.0%	0.6%	99.4%
Diesel	0.0%	0.0%	100.0%	0.0%	0.0%	0.6%	99.4%
LPG	0.0%	0.0%	0.0%	50.0%	50.0%		100.0%
Residual Oil	50.0%			50.0%			
Petroleum Coke	50.0%	0.0%	0.0%	50.0%	0.0%		

3.2 Engine Efficiency and Emissions

The fuel consumption or efficiency of engines affects GHG emissions because fuel is converted to CO_2 when combusted. Methane (CH_4) and nitrous oxide (N_2O) emissions also contribute to GHG emissions. Table 3 shows EPA's emission factors for non-road engines in the 20 to 100 hp range. The EER is calculated from the relative brake specific fuel consumptions in Table 4. N_2O emissions are estimated at 3% of NO_x[7] and are shown in Table 5. The NO_x emissions are comparable for LPG and gasoline. Diesel engine NO_x emissions are over 6 times higher. This result is potentially significant as N_2O has a higher global warming potential. However, no actual data on N_2O emissions were identified, only the documented assumption that their fraction of total NO_x is about 3%[5]. Therefore any conclusions regarding N_2O emissions must be considered tentative.

[7] Assumption in JEC TTW report; see footnote 4.

Table 3. EPA Emission Factors for Non-Road Engines

Fuel	BSFC (lb/hp-hr)	Emissions (g/hp-hr)			
		HC	CO	NO_x	PM
Gasoline, SI 4-stroke[1]	0.484	0.27	11.94	0.69	7.7
LPG, SI 4-stroke[1]	0.406	0.1	3.92	0.85	0.05
Diesel, CI[2]	0.408	0.6	2.5	5.0	0.6

[1]Exhaust Emission Factors for Non-road Engine Modeling - Spark-Ignition, EPA-420-P-10-019, July 2010. Phase 2 (post 2007)

[2]Exhaust Emission Factors for Non-road Engine Modeling - Compression-Ignition,
EPA Report No. NR-009A, June 1998. Tier 2 (post 2004)

Table 4. EER Calculated from BSFC

Fuel	LHV	BSCF					EER, relative to Gasoline
	(MJ/kg)	(lb/hp-hr)	(g/hp-hr)	(MJ/hp-hr)	(MJ/kWh)	(MJ_f/MJ_w)	
Gasoline, SI 4-stroke	43.45	0.484	220	9.538	12.79	3.55	1.00
LPG, SI 4-stroke	46.61	0.406	184	8.583	11.50	3.20	1.11
Diesel, CI	42.79	0.408	185	7.918	10.61	2.95	1.20

Table 5. N_2O Emissions Calculated from 3% of NO_x

Fuel	N_2O Emissions		
	(g/hp-hr)	(g/MJ)	(g CO_2e/MJ)
Gasoline, SI 4-stroke	0.0207	0.00217	0.65
LPG, SI 4-stroke	0.0255	0.002971	0.89
Diesel, CI	0.15	0.018944	5.65

Table 3 shows that the NO_x emissions from LPG engines, while comparable to those from gasoline engines, are slightly higher. The higher NO_x and lower CO emissions for LPG equipment are consistent with more efficient engines. Low CO emissions compared with gasoline reflect a higher combustion efficiency and conversion of fuel to energy. The higher NO_x emissions are consistent with higher combustion temperatures that also correspond to higher efficiency. Unfortunately, the data in Table 3 are aggregated emission factors and a comparison of like mower engines was not possible. The skewed efficiency results may reflect a broad class of engines and not riding mower engines specifically.

3.3 Upstream Fuel Cycle Emissions

Upstream fuel cycle emissions correspond to the energy inputs and emissions associated with feedstock production, transport, refining, and fuel delivery. These emissions are estimated with WTW models such as CA-GREET. Upstream fuel cycle emissions are proportional to fuel use and depend entirely on the type of fuel used. Differences between petroleum derived LPG, gasoline, and diesel correspond to assumptions on assignments of energy inputs for oil refining as well as differences in fuel delivery. Natural gas based LPG production is generally considered less energy intense than petroleum based product because the LPG occurs as a natural gas liquid. The energy required to recover LPG corresponds primarily to separation and compression.

4. LCA Results

CA GREET model results are given in Table 6 for LPG, gasoline, and diesel fuel as well as the WTW results adjusted for engine efficiency. Figure 3 shows the GHG emissions for LPG, gasoline, and diesel fuels from the CA GREET model. The results are disaggregated to show the contribution of transport and distribution.

Table 6. Final Disaggregated LCA GHG Emission Results by Fuel

<table>
<tr><th rowspan="2">Fuel Cycle Step</th><th colspan="4">GHG Emissions (g CO_2e/MJ fuel)</th></tr>
<tr><th>LPG, Natural Gas-Derived</th><th>LPG, Petroleum-Derived</th><th>ULSD</th><th>CARBOB, Petroleum</th></tr>
<tr><td>Feedstock Production</td><td>3.06</td><td>6.80</td><td>6.80</td><td>6.8</td></tr>
<tr><td>Feedstock Transport</td><td>0.456</td><td>1.231</td><td>1.231</td><td>1.231</td></tr>
<tr><td>Refining</td><td>4.6</td><td>4.6</td><td>11.4</td><td>13.79</td></tr>
<tr><td>Transport and Distribution</td><td>0.667</td><td>0.667</td><td>0.400</td><td>0.410</td></tr>
<tr><td>Vehicle</td><td>66.6</td><td>66.6</td><td>76.6</td><td>73.7</td></tr>
<tr><td>Total TTW</td><td>75.4</td><td>79.9</td><td>96.5</td><td>95.9</td></tr>
<tr><td rowspan="2"></td><td colspan="2">50% petroleum-derived LPG/50% NG-derived LPG</td><td></td><td></td></tr>
<tr><td colspan="2">77.6</td><td>96.5</td><td>95.9</td></tr>
<tr><td colspan="5">WTW with end use efficiency adjustment</td></tr>
<tr><td>EER</td><td>1.11</td><td>1</td><td>1.2</td><td>1</td></tr>
<tr><td>WTW GHG (g/MJ)</td><td>69.9</td><td>77.6</td><td>80.4</td><td>95.9</td></tr>
</table>

Figure 1 (discussed in Section 1) shows total summary results for a 50-50 mix of petroleum-derived and natural gas-derived LPG-fueled riding mowers compared to comparable gasoline and diesel-fueled mowers. Figure 1 also shows results if the efficiency improvement (increased EER) of LPG-fueled mowers is not realized. Even in such a case (the EER=1 bar in the figure), there is a reduction in GHG emissions due to the decreased carbon content and decreased upstream energy requirements of LPG alone compared to gasoline and diesel-fueled mowers.

Table 7 summarizes the GHG emission factor data from the above discussion in a units that are perhaps more familiar to LPG engine community.

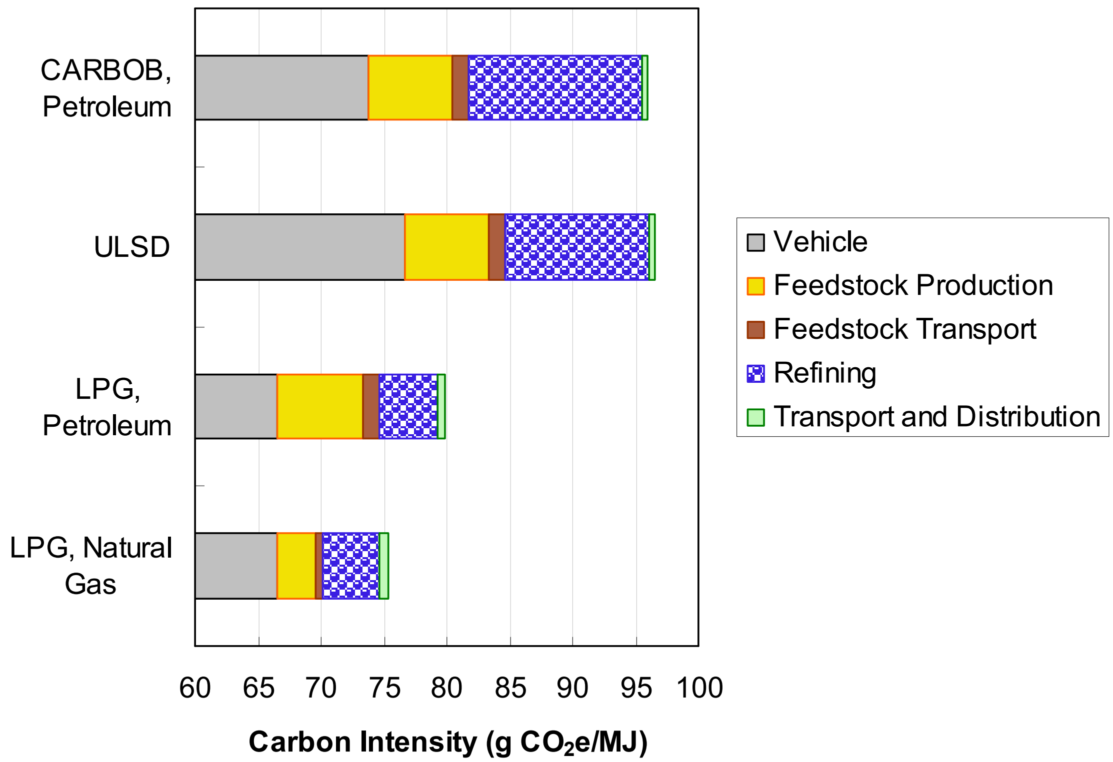

Figure 3. Comparison of Disaggregated WTW Emissions from LPG, Gasoline, and Diesel Fueled Engines in Riding Mower Applications

Table 7. Summary of GHG Emission Factors

Fuel	BSFC, Btu/hp-hr	EER	CI, g CO2e/MJ	CI, g CO2e/hp-hr
Gasoline, SI 4-stroke	9,039	1.00	95.9	915
LPG, SI 4-stroke[1]	8,134	1.11	69.9	600
	9,039	1.00	77.6	740
Diesel, CI[2]	7,505	1.20	80.4	637

5. Conclusions

The analysis of GHG emissions from small engines used in riding mower applications results in the following conclusions:

1. LPG-fueled engines used in riding mower applications have 27% lower GHG emissions, as measured by their carbon intensity (CI) expressed in g CO_2e/MJ fuel, than gasoline-fueled mowers in comparable applications. GHG emissions in LPG-fueled engines in

riding mower applications, at 70 g CO_2e/MJ fuel, are 26 g CO_2e/MJ fuel lower than the 96 g CO_2e/MJ fuel for gasoline applications. This results from a combination of reduced carbon content of LPG, reduced upstream energy requirements, and increased engine efficiency of LPG-fueled engines, this latter based on EPA data.

2. Even if no efficiency improvement is realized LPG-fueled engines used in riding mower applications have 20% lower GHG emissions than gasoline-fueled mowers in comparable applications. Without any efficiency improvement, GHG emissions in LPG-fueled engines in riding mower applications, at about 78 g CO_2e/MJ fuel, are 18 g CO_2e/MJ fuel lower than the 96 g CO_2e/MJ fuel for gasoline applications.
3. Compared to diesel-fueled engines in riding mower applications, GHG emissions reductions are 14% for comparable LPG-fueled engines, a reduction of 10 g CO_2e/MJ fuel from the 80 g CO_2e/MJ fuel for diesel mower engines.
4. Producing LPG from natural gas is less GHG emission intense than producing LPG via processing fuels in an oil refinery.
5. If LPG is treated as a co-product from oil refineries, the GHG emissions are even lower because the upstream energy requirements are zero for co-product LPG. These upstream emissions are allocated entirely to the gasoline and diesel fuel products from a refinery, instead of being allocated according to the energy content of each output (which would include the LPG as a refinery product).
6. EPA data shows significant efficiency improvement for LPG engines, which translates into substantially reduced GHG emissions. The validity of this assumption should be closely monitored by the LPG industry.