Program Record (Offices of Vehicle Technologies, Hydrogen and Fuel Cell Technologies, and Bioenergy Technologies)	
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Title: Life Cycle Greenhouse Gas Emissions for Small Sport Utility Vehicles	
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Item

This record documents the cradle-to-grave (C2G) and well-to-wheels (WTW) greenhouse gas (GHG)[4] emissions of light-duty vehicles, assuming key parameters for a variety of current (2020) and future (2050) vehicle-fuel technology pathways. WTW GHG emissions include fuel production, delivery and dispensing into a vehicle, and fuel consumption during vehicle operation. The vehicle manufacturing cycle includes impacts of raw material extraction, vehicle parts production, assembly, as well as its disposal and related materials recycling processes. C2G emissions are a sum of WTW emissions and emissions associated with vehicle manufacturing. As shown in Figure 2, using current technologies, all evaluated biofuel, battery electric, and hydrogen fuel cell vehicle pathways offer significant C2G GHG emissions reduction compared to the current gasoline internal combustion engine vehicle. The C2G GHG emissions for a more comprehensive vehicle/fuel pathways are provided in Appendix A.

Background

The C2G GHG emissions results in Figure 2 were generated using Argonne's Greenhouse gas, Regulated Emissions, and Energy use in Technologies (GREET®) model,[5] with inputs of fuel economy and vehicle component sizing provided by Argonne's Autonomie model.[6] Figures 3 and 4 below show the WTW GHG emissions[7] results for various fuels and energy sources in g CO_{2e}/MJ_{fuel}, and emissions for the vehicle manufacturing cycle in metric tons (MT) CO_{2e}/vehicle, respectively. In order to compare total C2G emissions across powertrains per service unit basis (g CO_{2e}/mi), the WTW GHG emissions are multiplied by the vehicle's fuel

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[4] GHG emissions are the sum of the CO_2 equivalent (CO_{2e}) emissions of three gases, CO_2, CH_4, and N_2O, weighted by their 100-year global warming potentials of 1, 30 and 265, respectively.
[5] GREET 2020, https://greet.es.anl.gov/
[6] https://www.autonomie.net/
[7] The WTW GHG emissions per unit of fuel's lower heating value is also known as the carbon intensity (CI) of the fuel.

consumption (MJ_{fuel}/mi), and the GHG emissions for the vehicle manufacturing cycle is allocated over 183,000 miles.

The WTW and C2G emissions are depicted for two scenarios, current and future. The current scenario represents use of state-of-the-art vehicle technologies in 2020, while the future scenario represents vehicle technologies that are assumed to have met DOE performance targets by 2050. Key assumptions for these two scenarios (e.g., powertrain efficiency, component weights, etc.) were provided by the three U.S. Department of Energy Transportation Offices (Vehicle Technologies Office, Hydrogen and Fuel Cell Technologies Office, and Bioenergy Technologies Office), within the Office of Energy Efficiency and Renewable Energy, and were incorporated into Autonomie to determine the fuel economy for each vehicle technology (Table 1). The fuel economy and vehicle component weights were then incorporated into GREET to determine the WTW and C2G GHG emissions.

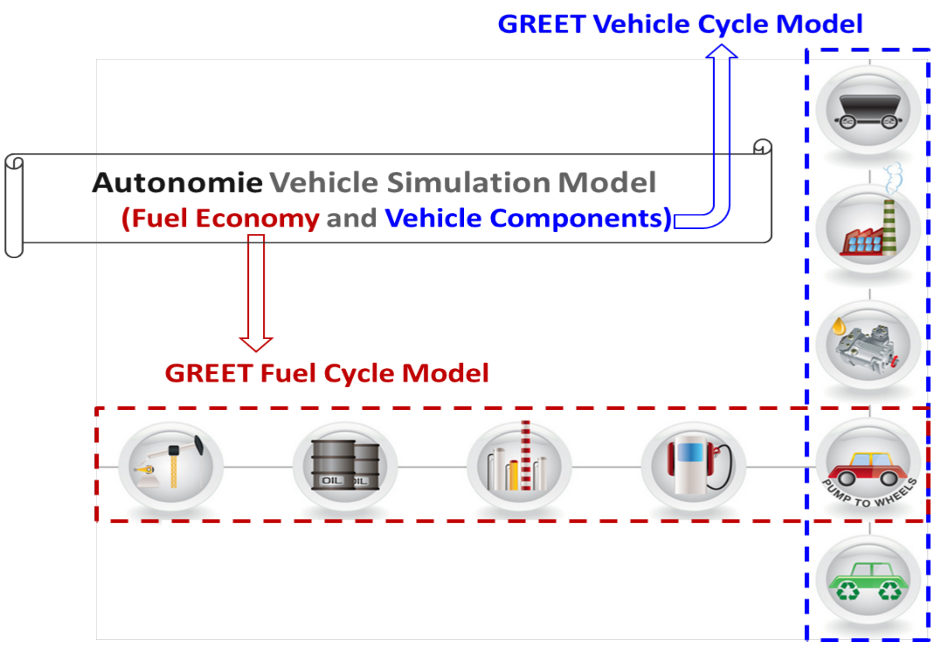

Figure 1. Cradle-to-Grave (C2G) Analysis Framework

The WTW GHG emissions in Figure 3 are the sum of emissions associated with the feedstock and fuel production (i.e., "well-to-pump" [WTP]), as well as fuel use during vehicle operation (i.e., "pump-to-wheel" [PTW]). The net CO_2 uptake from the atmosphere to grow bio-feedstock is embedded in the "Feedstock and Fuel Production" emissions of the biofuels and their blends. Gasoline consists of 10% corn-ethanol blended with petroleum gasoline blendstock, by volume (E10), for use in spark-ignition (SI) internal combustion engine vehicles (ICEV) and hybrid electric vehicles (HEV). Diesel is assumed to be of low-sulfur content (<15 ppm), for use in compression-ignition (CI) ICEV. Corn and corn stover E85 represent a blend of 85% corn-ethanol blended with petroleum gasoline blendstock, by volume, for use in SI ICEV. Pyrolysis of forest residue is modeled as a drop-in renewable fuel that can replace petroleum gasoline. Cellulosic biomass pathways such as corn stover ethanol and pyrolysis of forest residue have lower carbon intensity compared to corn ethanol due to lower GHG emissions in the growth phase and conversion processes.

Emissions associated with electricity used for battery charging are based on three generation scenarios: the average United States (US) grid mix, a California (CA) average grid mix, and renewable electricity. Vehicles requiring battery recharging include battery electric vehicles and plug-in hybrid electric vehicles (PHEVs).

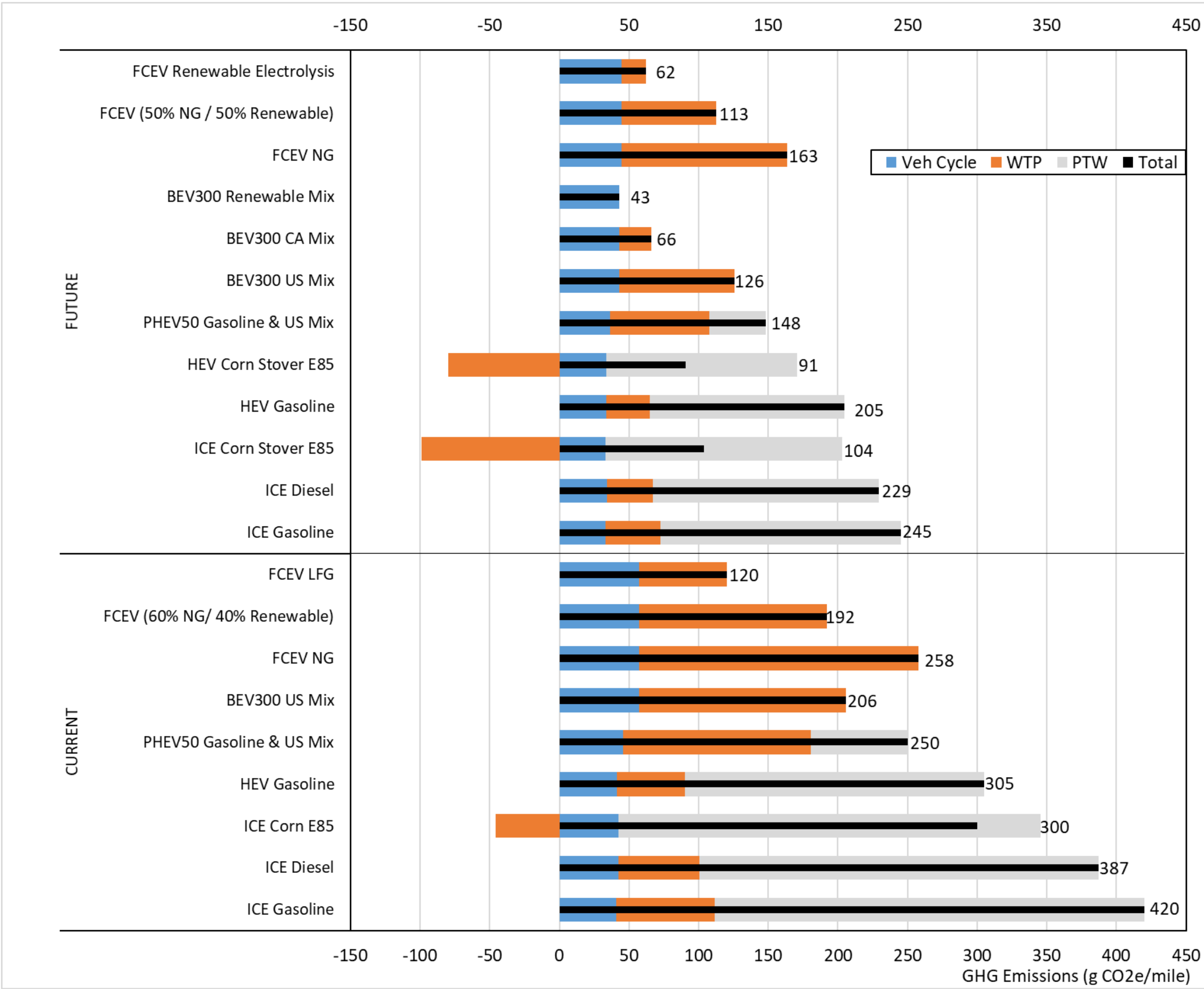

Figure 2. Life Cycle GHG Emissions (g CO_{2e}/mi) for Selected Current (2020) and Future (2050) Fuels and Vehicle Technologies for Small SUVs

Hydrogen for use in fuel cell electric vehicles (FCEVs) can be sourced from several pathways. "FCEV NG" represents the use of hydrogen produced entirely via steam methane reforming (SMR) of natural gas. "FCEV renewable electrolysis" represents the use of hydrogen produced via polymeric exchange membrane (PEM) electrolysis, using 100% renewable electricity. "FCEV LFG" represents the use of hydrogen produced through reforming of methane sourced from landfill gas (LFG). For both the current and future scenarios, hydrogen production was also modeled to represent blends of hydrogen from steam methane reforming and electrolysis.[8] In all hydrogen pathways, it is assumed that hydrogen delivery, compression, and precooling at

[8] The renewable content of hydrogen fuel dispensed to light duty vehicles in California in 2020 was approximately 40%. Per state legislation, the network of publicly funded hydrogen fueling stations in California is required to dispense hydrogen with at least a 33% renewable content. Minimum renewable content for future stations is estimated at 40%. [Source: "2020 Annual Evaluation of Fuel Cell Electric Vehicle Deployment & Hydrogen Fuel Station Network Development." California Air Resources Board. September 2020. https://ww2.arb.ca.gov/sites/default/files/2020-09/ab8_report_2020.pdf]

fueling stations will draw power from the U.S. grid mix. The hydrogen is assumed to be transported via pipeline to fueling stations.[9] It is noted that, while hydrogen from natural gas and the current U.S. electricity mix have amongst the highest WTW GHG emissions per unit of fuel energy (i.e., per MJ) as shown in Figure 3, FCEVs and BEVs are 2–4X more efficient than ICEVs. As a result, their C2G GHG emissions per mile are considerably lower than ICEVs, as shown in Figure 2.

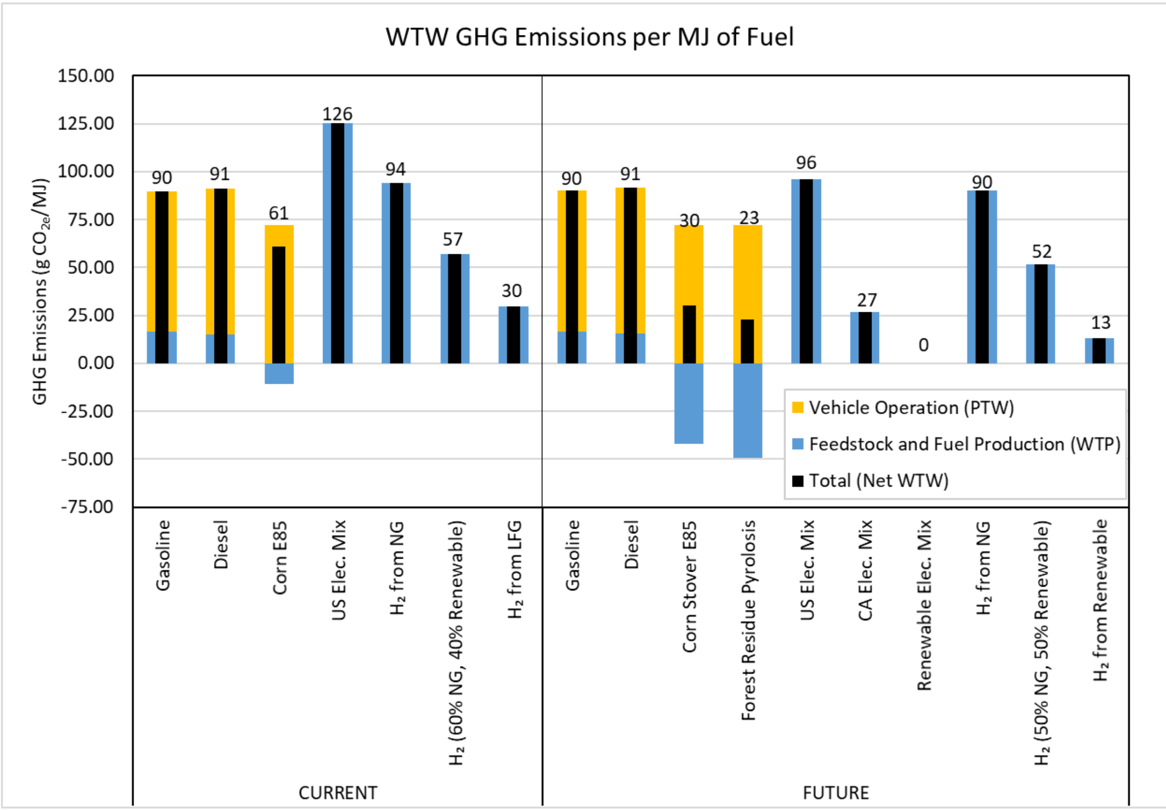

Figure 3. WTW GHG Emissions for Current (2020) and Future (2050) Fuel Technology Pathways

In Figure 4, the vehicle manufacturing cycle GHG emissions for the body and chassis are similar across vehicle powertrains for both current and future technologies. The body and chassis combined here represent the typical "glider" approach used in other literature. The small differences in emissions associated with body and chassis observed in Figure 4 between different powertrains are noteworthy and represent a simplification in the present modeling approach, which is based on linear scaling of the base-level mass while maintaining material compositions. The battery is a major contributor to GHG emissions for BEVs with real-world driving ranges of 200, 300, and 400 miles (i.e., BEV200, BEV300 and BEV400), as well as for extended range electric vehicles with 50 miles range (i.e., PHEV50). A battery chemistry of NMC811[10] is assumed for all BEV and PHEV. The carbon fiber overwrapped, 700 bar, hydrogen onboard storage is a major contributor to the GHG emissions of FCEV manufacturing. It is important to note that the method by which emissions are allocated to raw materials that

[9] Pipeline delivery was assumed because it may become a mainstream pathway for hydrogen delivery to mature markets in the future. Current fueling stations source hydrogen from tube trailers and liquid hydrogen tankers. Several hydrogen liquefaction plants in North America currently source power from hydropower.
[10] Ni:Mn:Co = 8:1:1

comprise a vehicle affects the overall vehicle cycle emissions. In this record, energy and emissions associated with the mining of critical materials for batteries and fuel cells (e.g., lithium, cobalt, platinum, etc.) have been evaluated on a mass allocation basis (i.e., mass share of all mined materials) for consistency with other DOE analyses.

As shown in Figure 4, the total vehicle manufacturing cycle GHG emissions are in the range of 8–12 metric tons (MT) of CO_{2e} for current powertrain technologies, and 6–9 MT of CO_{2e} for future powertrain technologies. On a per-mile basis, the vehicle manufacturing cycle is between 40–70 and 30–50 g CO_{2e}/mi for current and future technologies, respectively, as previously shown in Figure 2. The generally lower vehicle cycle GHG emissions for future vehicles compared to current vehicles are due to the assumed improved aerodynamics and lighter component weight of future vehicle systems, both of which improve fuel economy and reduce the quantity of fuel stored onboard. It is important to note that material compositions of powertrain components (e.g., platinum loading of fuel cells, battery chemistries) may change in the future, and the emissions intensity of each material may change as well. These potential changes were not modeled in the current analysis.

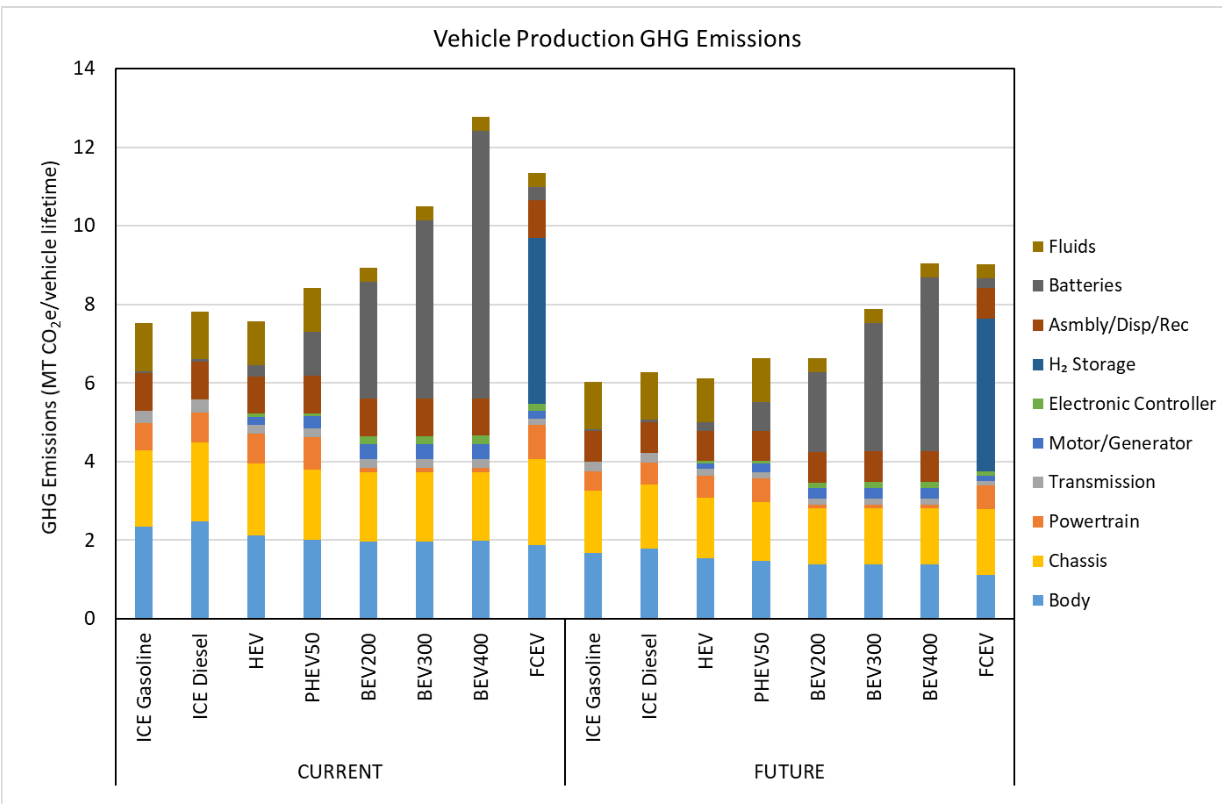

Figure 4. Total Vehicle Manufacturing Cycle GHG Emissions for Current (2020) and Future (2050) Vehicle Powertrain Technologies for Small SUVs

Assumptions

The below tables indicate the key parameters driving the life cycle GHG emissions results for the various fuels and vehicle powertrain technologies.

Table 1. Key Assumptions for Vehicle Fuel Economy

	MPGGE* (2020)			MPGGE* (2050)		
Small SUV	**ICEV and HEV**	**PHEV-CS†**	**PHEV & BEV-CD‡**	**ICEV and HEV**	**PHEV-CS†**	**PHEV & BEV-CD‡**
Conventional SI Turbo	28			50		
Conventional CI	31			55		
Split HEV	40			62		
Fuel Cell HEV	64			104		
PHEV50•		38	87		66	143
BEV200			105			165
BEV300			100			154
BEV400			91			151

• PHEV = a plug-in hybrid configuration where a gasoline engine extends the vehicle's driving range after the battery is depleted
* MPGGE = miles per gasoline gallon equivalent assuming lower heating value of 112,194 Btu per gallon of E10 gasoline
† CS = charge sustaining mode
‡ CD = charge depleting mode. Autonomie assumes charging efficiency of 88%.

Table 2. Key Assumptions for the Generation Mix for PHEV and BEV Recharging

		Residual Oil	Natural Gas	Coal	Nuclear	Biomass	Renewables
2020	**US**	0.4%	36.8%	22.8%	20.3%	0.3%	19.4%
	CA	0.0%	35.0%	0.0%	10.9%	1.2%	52.9%
2050	**US**	0.1%	35.1%	14.3%	12.9%	0.3%	37.3%
	CA	0.0%	15.6%	0.0%	0.0%	1.2%	83.2%

Table 3. Key Assumptions for Hydrogen Production and Refueling

	Production Efficiency (LHV basis)	Steam Byproduct	Fueling Electric Energy Use*
NG SMR	72%	145,000 (Btu/mmBtu$_{H2}$)	3 (kWh/kg$_{H2}$) for compression to 950 (bar) and pre-cooling to -40°C
Water Electrolysis[11]	66% or 50 (kWh/kg $_{H2}$)	N/A	

* GHG emissions associated with electricity use for fueling of FCEV is based on U.S. grid average generation mix

[11] https://www.hydrogen.energy.gov/pdfs/19009_h2_production_cost_pem_electrolysis_2019.pdf

Table 4. Key Assumptions for the Biofuels Analysis

	Corn Ethanol (Dry Mill)	Corn Stover (CS) Ethanol[12]	Catalytic Fast Pyrolysis of Forest Residue Blend (FR)[13]
Farming / Collection Energy Use	6,588 (Btu/bushel)	192,500 (Btu/dry ton*)	139,910 (Btu/dry ton)
Plant Energy Use	26,371 (Btu/gal)	180 (Btu diesel/gal)	45,000 (Btu/GGE)[14]
Fuel Product Yield	2.95 (gal EtOH†/bushel)	79 (gal EtOH/dry ton)	61.56 (GGE/dry ton)[15]
Co-products	5.36 (lb DGS‡/gal) 0.19 (lb corn oil/gal)	1.8 (kWh_e/gal)	3.54 kWh_e/GGE 1.1 lb/GGE (MEK**+Acetone)
Land Use Change (LUC)	7.4 (g CO_{2e} /MJ)	-0.6 (g CO_{2e}/MJ)	None

* ton = short ton
** MEK = Methyl Ethyl Ketone
† EtOH = Ethanol
‡ DGS = Distillers' grain solubles

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12 https://www.osti.gov/biblio/1013269 and https://www.nrel.gov/docs/fy11osti/47764.pdf
13 Based on 50/50 blend of logging residue and clean pine, https://www.osti.gov/biblio/1616516 and https://www.osti.gov/servlets/purl/1605092
14 Combined NG use in the biorefinery and the petroleum refinery
15 https://www.nrel.gov/docs/fy15osti/62455.pdf, GGE = 112,194 Btu

Appendix A

Life Cycle GHG Emissions (g CO_2e/mi) for Current (2020) and Future (2050) Fuels and Vehicle Technologies for Small SUVs